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Performance-Driven Generative Design for Daylighting Optimization in a Tangerang Aerotropolis Office Building

Sultan Yazid[1]*, Melania Lidwina Pandiangan[2], Lutfi Aulia Makarim[3]
[1,2] Department of Architect Profession Education, Faculty of Technology and Design, Universitas Pembangunan Jaya, South Tangerang, Indonesia
[3] Department of Architecture, Faculty of Technology and Design, Universitas Pembangunan Jaya, South Tangerang, Indonesia

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Corresponding Author:
Sultan Yazid
Department of Architect Profession Education, Faculty of Technology and Design, Universitas Pembangunan Jaya, South Tangerang, Indonesia
Email: sultan.yazid@upj.ac.id

Abstract

Daylighting in tropical climates may increase glare risk in office buildings. This issue is particularly relevant in the Tangerang Aerotropolis area, where humid tropical conditions and airport operational safety regulations constrain building development. This study optimized daylighting performance in an office building using a Performance-Driven Generative Design approach. The workflow integrated Rhinoceros 3D, Grasshopper, ClimateStudio, and Galapagos to evaluate six envelopes and building mass variables. The optimization evaluated 950 design alternatives across 18 generations using $UDI_{100–3000}$ as the objective function. A maximum $UDI_{100–3000}$ of 95.5% was achieved with a WWR of 0.47, window height of 2.53 m, shading spacing and depth of 0.40 m, building width of 12 m, and orientation of 76°. Best-performing configurations converged within WWR 0.40–0.47, window height 2.50–2.60 m, shading spacing 0.30–0.50 m, shading depth 0.30–0.40 m, building width 12–13 m, and orientation 72°–84°. The results identified a high-performing configuration and recurring parameter ranges among the best-performing solutions.

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INTRODUCTION

Daylighting is one of the key aspects of office building design, because the visual quality of indoor spaces and the comfort of office occupants are influenced by daylighting (Karimimoshaver & Derakhshan, 2026). Adequate access to daylight can support visual activities while reducing the need for artificial lighting during daytime hours (Atthaillah et al., 2023). Therefore, daylighting has become a primary consideration in the design of buildings that respond to climatic conditions and user needs.

In humid tropical regions, efforts to increase access to daylight are often accompanied by a higher risk of glare and visual discomfort (Salem Bahdad et al., 2022). Under these conditions, the building envelope functions to maximize daylight admission and to regulate its distribution so that illuminance levels remain suitable for occupant activities (Setiawan & Elsiana, 2025). Design parameters that influence daylighting performance include the Window-to-Wall Ratio (WWR), opening dimensions, building orientation, shading devices, and building mass proportions (Purghorbani & Bagheri Sabzevar, 2026).

Daylighting performance is affected by the interaction of multiple interrelated design parameters. Changes in one parameter may influence the performance of others, resulting in relationships that are not always linear (Fernández et al., 2015). In design practice, daylighting quality is determined by a combination of design decisions that operate simultaneously (Hashemi et al., 2025). This condition highlights the importance of an approach capable of systematically evaluating multiple combinations of design parameters to achieve optimal daylighting performance.

This context is particularly relevant to the Tangerang Aerotropolis area surrounding Soekarno–Hatta International Airport, as illustrated in Figure 1 by the red delineated boundary. The study area is located at approximately 6°08′50.1″ S and 106°37′13.3″ E, within the broader aerotropolis development area of Tangerang. The area represents one of the major urban development zones dominated by commercial and office functions (Adrian

et al., 2017). In addition to the challenges associated with a humid tropical climate, building development in this area is also constrained by Airport Operational Safety Zone regulations, which limit building height. These restrictions reduce the flexibility of vertical development, making building performance increasingly dependent on the configuration of building mass and envelope design.

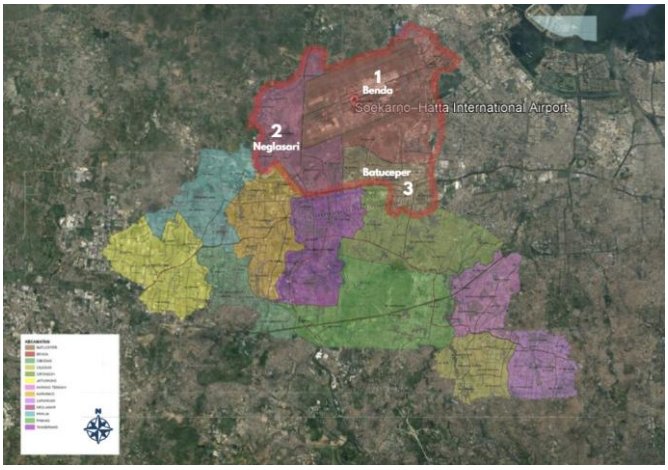


Fig 1. Aerotropolis Soekarno-Hatta Airport Area

Advances in computational technology in architecture have enabled daylighting performance to be evaluated digitally from the early stages of the design process (Reinhart & Cerezo Davila, 2016). One of the approaches commonly used is Climate-Based Daylight Modelling (CBDM), a daylighting evaluation method that utilizes annual weather data specific to a given location (Wang et al., 2024). This approach enables daylighting performance to be assessed based on variations in weather conditions throughout the year, resulting in a more representative evaluation of actual building conditions. Daylight performance can be assessed using various metrics, including illuminance-based metrics and annual climate-based indicators such as Useful Daylight Illuminance (UDI) (Mardaljevic et al., 2017), spatial Daylight Autonomy (sDA), and Annual Sunlight Exposure (ASE). The selection of an appropriate metric depends on the performance aspect being investigated and the objectives of the design evaluation.

In addition to advancements in simulation methods, parametric approaches have created opportunities to evaluate a large number of design alternatives. The integration of parametric modelling and performance simulation enables the relationship between design decisions and building performance to be systematically analyzed through automated processes (Antunes et al., 2025). These developments have led to the emergence of the Performance-Driven Generative Design (PDGD) approach, a design exploration method that integrates parametric modelling, performance simulation, and optimization algorithms to generate design alternatives based on specific performance objectives (Caetano et al., 2020).

Daylighting performance can be evaluated by varying one or several design parameters, such as the Window-to-Wall Ratio, building orientation, or shading device configuration. Such approaches have provided valuable insights into the relationship between design parameters and daylighting performance. However, since daylighting performance results from the interaction of multiple design decisions, evaluations based on a limited number of selected scenarios may not represent the full range of possible parameter combinations encountered during the design process. This condition highlights the potential of optimization approaches capable of simultaneously exploring multiple combinations of design parameters.

Although previous studies have demonstrated the application of parametric modelling and genetic algorithms to daylighting optimization, this study further investigates the optimization process by tracking the best-performing design configurations across successive generations and examining the convergence of multiple design parameters as integrated design configurations. Based on this context, the study investigates daylighting performance optimization in office buildings within the Tangerang Aerotropolis area using a PDGD approach. It focuses on exploring the relationships between building and façade design parameters and daylighting performance through an iterative optimization process.

LITERATURE REVIEW

The literature review in this study focuses on three main aspects that form the foundation of the daylighting optimization process: design parameters influencing daylighting performance, climate-based daylighting evaluation methods, and the PDGD approach for performance-based design exploration.

Design Variables Affecting Daylight Performance

Daylighting performance within buildings is influenced by various design parameters related to building envelope configuration and building mass proportions. These parameters determine the amount of daylight entering the space, the distribution of illuminance, and the depth of daylight penetration (Mashaly et al., 2025).

One of the most used parameters in daylighting evaluation is the Window-to-Wall Ratio (WWR) (Jia et al., 2023). WWR defines the proportion of window areas relative to the building façade area and therefore affects the amount of daylight that can enter the interior space. In addition to window area, window height also influences the ability of daylight to reach deeper areas within a space, as it is related to the angle of daylight penetration and the distribution of illuminance across the work plane (Sangtarash et al., 2022).

Building orientation is another parameter that affects daylighting characteristics (Shamsuddin et al., 2026). Differences in orientation result in variations in solar exposure throughout the day and across the year, which may lead to different daylighting performance outcomes even when similar window configurations are applied (Shamsuddin et al., 2026).

Daylighting performance is also influenced by the use of shading devices (Lim et al., 2026). In tropical office buildings, horizontal shading devices are widely used because they are effective in controlling solar penetration at high sun angles commonly found in regions near the equator (Mangkuto et al., 2022). Geometric characteristics of shading devices, such as spacing between elements and shading depth, can affect the distribution of illuminance within interior spaces (Kirimtat et al., 2019).

In addition to building envelope parameters, building mass proportions also play an important role in daylighting quality. Building width (Elsiana et al., 2024) determines the penetration distance of daylight from the openings to the deepest areas of the interior. Buildings with slimmer floor plates generally allow for a more uniform distribution of daylight compared to buildings with greater depths (Mustafa, 2024).

Table 1. Synthesis of Building Envelope and Mass Design Parameters Affecting Daylighting Performance

No.	Design Parameter	Primary Impact on Performance	Reference
1	*Window-to-Wall Ratio* (WWR)	WWR strongly influences daylight sufficiency; reported suitable ranges vary by orientation, with 30–50% for south-facing and 60–70% for north-facing classrooms in one simulation study. Excessive WWR may increase over-illumination.	(Jia et al., 2023)
2	Window Height	Increasing window height generally improves spatial daylight sufficiency and daylight penetration, although its effect depends on room geometry and façade orientation.	(Sangtarash et al., 2022)
3	Building Width	Shallower spaces generally improve daylight sufficiency; preferred conditions were reported at depths below 14–15 m, depending on façade orientation and room geometry.	(Elsiana et al., 2024); (Mustafa, 2024)
4	Building Orientation	Orientation determines the magnitude and timing of direct solar exposure, requiring façade-specific responses to balance daylight availability and excessive solar exposure.	(Shamsuddin et al., 2026)
5	Horizontal Shading Spacing	Spacing controls the density of shading elements and daylight penetration; excessively dense configurations can obstruct useful daylight. A parametric study in Indonesia identified 0.50 m spacing among the highest-performing configurations.	(Kirimtat et al., 2019)
6	Horizontal Shading Depth	Increasing shading depth reduces direct solar penetration; depths beyond 2.0 m showed limited additional daylight-performance benefit in tropical classroom simulations.	(Mangkuto et al., 2022); (Lim et al., 2026)

Based on the literature review summarized in Table 1, six key parameters were identified as influencing daylighting performance in buildings. These parameters include the Window-to-Wall Ratio (WWR), window height, building width, building orientation, horizontal shading spacing, and horizontal shading depth. All these parameters were subsequently employed simultaneously as design variables in the simulation and optimization process conducted in this study.

Climate-Based Daylight Modelling and Useful Daylight Illuminance

Climate-Based Daylight Modelling (CBDM) is a daylighting evaluation approach that utilizes location-specific annual climate data to simulate daylighting conditions throughout the year (Grobe & Jakubiec, 2023). Unlike static approaches that rely on a single sky condition, CBDM considers variations in weather conditions and solar position, resulting in a more representative evaluation of actual building performance.

CBDM uses Typical Meteorological Year (TMY) data, which contain annual climatic information such as global horizontal radiation, direct normal radiation, diffuse horizontal radiation, air temperature, relative humidity, wind direction, and wind speed (Rady et al., 2025). These data enable simulations to be conducted based on environmental characteristics that accurately reflect the study's location.

Several daylight indicators have been developed to evaluate daylighting performance using CBDM, including Daylight Autonomy (DA), Spatial Daylight Autonomy (sDA), Annual Sunlight Exposure (ASE), and Useful Daylight Illuminance (UDI). Each of these indicators employs different threshold values and evaluation objectives (Ukpong et al., 2025):

- Daylight Autonomy (DA): Measures the percentage of annual occupied hours during which a specific point within a space receives daylight illuminance above a defined minimum threshold (typically 300 lux) without the assistance of electric lighting (Ghalati & Tabatabaeiyan, 2025).
- Spatial Daylight Autonomy (sDA): A spatial extension of DA that calculates the percentage of floor area achieving a target illuminance level (e.g., 300 lux) for at least 50% of the annual occupied hours. This metric represents daylight sufficiency within a space (Gagne & Andersen, 2012).
- Annual Sunlight Exposure (ASE): Measures the percentage of floor area receiving excessive direct sunlight exposure (above 1000 lux) for more than 250 hours per year. This indicator is used to predict the risk of glare and excessive thermal loads in buildings (Lee et al., 2026).
- Useful Daylight Illuminance (UDI): Measures the percentage of time throughout the year during which daylight illuminance on the work plane remains within a range considered beneficial for human visual activities. The original UDI classification defined underlit (<100 lux), useful (100–2,000 lux), and overlit (>2,000 lux) conditions (Nabil & Mardaljevic, 2006). This classification was subsequently refined into four categories, distinguishing underlit (<100 lux), UDI-supplementary (100–300 lux), UDI-autonomous (300–3,000 lux), and overlit (>3,000 lux) conditions (Mardaljevic et al., 2017).

(Lou et al., 2025) UDI provides an alternative approach for characterizing daylight availability by considering the proportion of time during which illuminance falls within defined ranges. Its classification into underlit, useful, and over lit conditions allows daylight conditions to be described across different illuminance ranges rather than focusing on a single threshold. These characteristics make UDI relevant to studies investigating the distribution and temporal variation of daylighting performance under climate-based simulation conditions.

Performance-Driven Generative Design

Performance-Driven Generative Design (PDGD) is a design approach that integrates parametric modelling, performance simulation, and optimization algorithms to generate design alternatives based on specific performance objectives (Huang et al., 2025). In this approach, building performance serves as the basis for decision-making throughout the design exploration process.

PDGD enables the relationship between design parameters and building performance to be evaluated systematically through the integration of parametric modelling and digital simulation (Nembrini et al., 2014). Each modification of a design parameter generates performance feedback that can be used to assess the quality of the resulting design alternative.

One of the optimization methods applied in PDGD is the Genetic Algorithm (GA). This method operates through an evolutionary process consisting of selection, crossover, and mutation to generate new populations of solutions with improved performance compared to previous generations (Li et al., 2017). Genetic Algorithms are capable of exploring large solution spaces and handling non-linear relationships among design parameters (Mu, 2025).

In the context of daylighting, the PDGD approach enables multiple design parameters to be evaluated simultaneously, allowing the optimization process to extend beyond a limited number of predefined design scenarios (Baharvand et al., 2024). This approach provides opportunities to understand parameter tendencies that consistently produce high-performance outcomes.

Based on this review, the present study applies a PDGD approach to optimize daylighting performance through the integration of six design parameters: Window-to-Wall Ratio, window height, horizontal shading spacing, horizontal shading depth, building width, and building orientation, using $UDI_{100–3000}$ average value as the objective function.

METHODS

This study employed a PDGD approach to optimize daylighting performance in an office building located within the Tangerang Aerotropolis area. The approach integrated parametric modelling, CBDM simulation, and Genetic

Algorithm-based optimization into a unified and interconnected workflow. The optimization process simultaneously varied six geometric and façade design parameters and evaluated their effects on daylighting performance using $UDI_{100–3000}$ average value.

Research Workflow

The study was conducted using a PDGD approach that links a parametric model with building performance simulation and a Genetic Algorithm-based optimization process. In this approach, design parameters were explored simultaneously to generate multiple design alternatives that can be automatically evaluated based on the selected performance indicator.

The research process began with the development of a parametric office building model based on design conditions within the Tangerang Aerotropolis area. The parametric model was then linked to design variables that could dynamically vary according to predefined optimization ranges. Each generated combination of parameters was subsequently evaluated using CBDM simulation to obtain the $UDI_{100–3000}$ average value as the daylighting performance indicator.

The $UDI_{100–3000}$ average values, calculated as the arithmetic mean of the $UDI_{100–3000}$ values at all measurement points for each simulated design alternative, obtained from the simulations, were used as the objective function in the optimization process through the Genetic Algorithm implemented in Galapagos. The optimization proceeded iteratively through the generation of design populations, performance evaluation, and solution evolution until the best-performing design configuration was identified. In addition to determining the optimum solution, the study also analyzed population convergence patterns to identify parameter ranges that consistently produced high daylighting performance. The overall research workflow is illustrated in Figure 2.

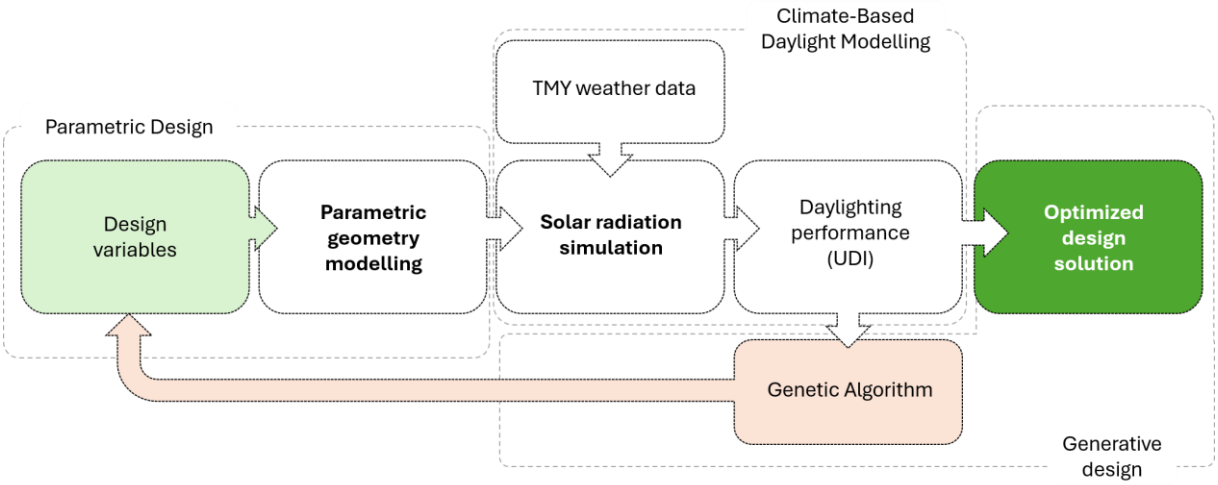


Fig 2. Research Workflow

Building Model and Optimization Variables

The study was conducted on an office building model representing design conditions within the Tangerang Aerotropolis area. This area was selected because it is one of the major commercial and business development zones located within the influence of the Airport Operational Safety Zone (KKOP) regulations surrounding Soekarno-Hatta International Airport (Dinas Perhubungan Kabupaten Tangerang, 2022). These constraints make the optimization of building massing and envelope configurations particularly important for improving indoor environmental quality without relying on vertical building development. At the same time, the humid tropical climate of the area creates a specific daylighting challenge, as increasing daylight access through larger openings may also increase the potential for excessive illuminance and visual discomfort. Therefore, the combination of climatic conditions and restrictions on vertical development makes daylight-responsive optimization of building massing and envelope configurations particularly relevant in this context. The study location and the climate data source used in the simulations are shown in Figure 3.

Daylighting performance was evaluated using TMY climate data for Tangerang City, which represents the annual weather conditions of the study location. These data were employed in the CBDM simulations to generate daylighting performance assessments that account for variations in weather conditions throughout the year (Sun et al., 2023).

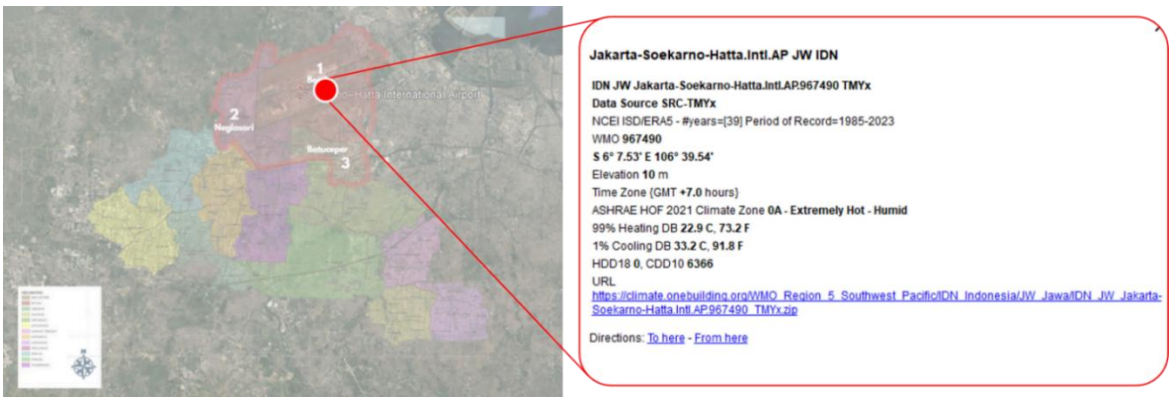


Fig 3. Study Location and TMY Climate Data Source for Tangerang City

The climate data used in the simulation were obtained from the Jakarta–Soekarno-Hatta International Airport TMY weather file, representing the climatic conditions of the study area. The dataset included direct, diffuse, and global horizontal radiation, with corresponding values of 878 Wh/m², 404 Wh/m², and 985 Wh/m², respectively (Fig 4). These radiation components were incorporated into the CBDM workflow to represent varying sky conditions throughout the year. The annual daylight simulations employed the Perez all-weather sky model, which uses direct and diffuse irradiance from the climate data to characterize hourly sky conditions.

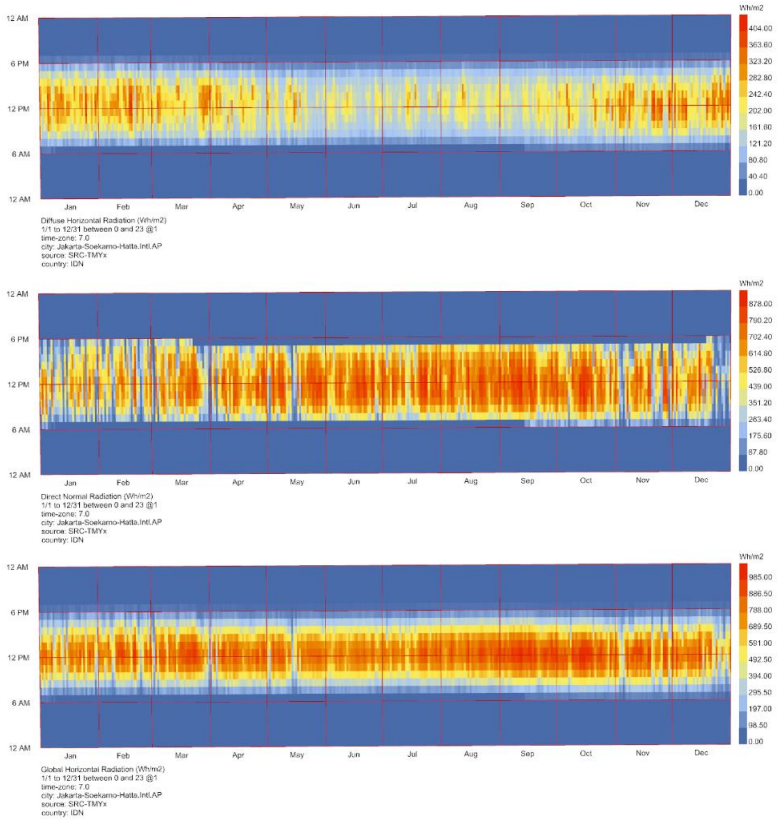


Fig 4. Annual Solar Radiation Profiles from the TMY Climate Data for Tangerang City

The research model consisted of a seven-story office building developed parametrically within the Rhinoceros 3D and Grasshopper environment. Parametric modelling enabled design parameters to be modified automatically during the optimization process, allowing multiple design alternatives to be generated and evaluated systematically. The variables considered in this study included opening parameters, shading devices, building mass proportions, and building orientation. The design variables identified in the literature review were subsequently implemented as optimization parameters in the parametric model (Table 2). The design variables constituted the variable inputs of the optimization process, whereas the TMY weather data, material properties, analysis-plane height, measurement-point spacing, and simulation settings were maintained consistently across the generated design alternatives. The primary output of the optimization was the daylighting performance value derived from the $UDI_{100–3000}$ results.

Building orientation was defined within a range of 0-90°, where 0° represented the longitudinal axis of the building aligned with the north–south axis, while 90° represented alignment with the east–west axis. Openings were distributed across all four building façades, allowing the tested orientation range to represent the building rotation relative to solar exposure from all cardinal directions. Given the rectangular and symmetrical configuration of the building model, orientations beyond 90° were considered geometrically redundant. The range of values for each parameter was determined based on tropical office building design considerations and the geometric constraints of the parametric model.

Table 2. Optimization Variables and Parameter Ranges

Parameter	Window-to-Wall Ratio (WWR)	Window Height	Horizontal Shading Spacing	Horizontal Shading Depth	Building Width	Building Orientation
Range	0.30–0.50	2.20–3.00 m	0.30–1.50 m	0.00–1.00 m	12–40 m	0–90°
Increment	0.01 %	0.01 m	0.01 m	0.10 m	1 m	1°

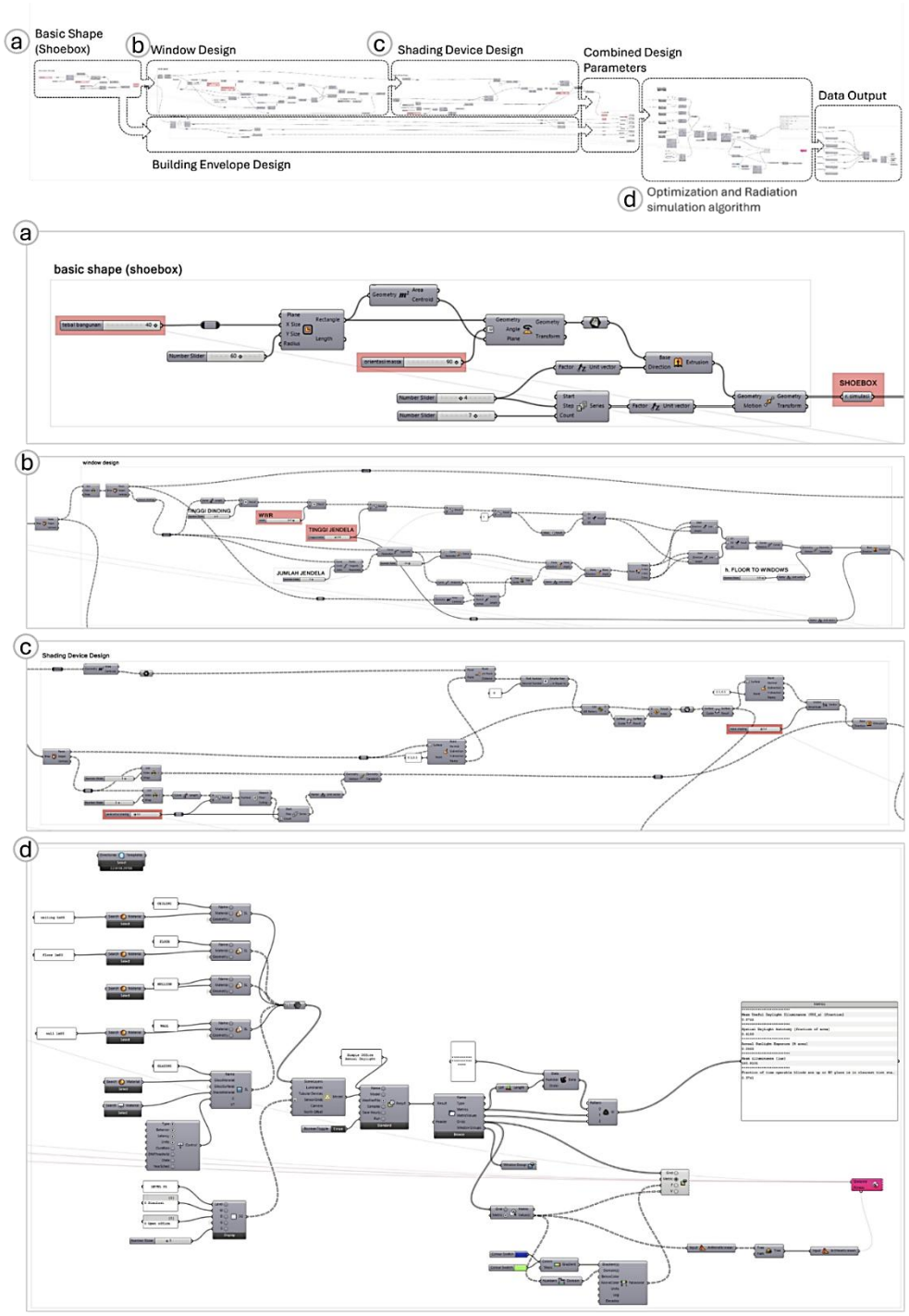


Fig 5. Parametric Model Structure Developed in Grasshopper

All these parameters were integrated into a parametric model developed using Rhinoceros 3D and Grasshopper. The structure of the parametric model employed in this study is illustrated in Figure 5. The model was developed progressively, beginning with the creation of a basic building mass (shoebox model) (Alsukkar et al., 2025), It was subsequently expanded through the addition of opening parameter controls, shading device configurations, building envelope development, design parameter integration, simulation and optimization processes, and output processing and visualization. This approach enabled all design parameters to be modified simultaneously during the optimization process, allowing a wide range of design combinations to be explored efficiently within a large solution space.

Simulation and Optimization Process

Daylighting performance was evaluated using ClimateStudio integrated with Grasshopper. The simulations were conducted using a CBDM approach and employed TMY climate data for Tangerang City, while the accuracy of the software's ray-tracing algorithm has been experimentally validated (Jones, 2017). Each design alternative generated by the parametric model was evaluated to obtain a $UDI_{100–3000}$ average value as the daylighting performance indicator.

The ClimateStudio daylight simulation workflow consisted of three major input groups: geometric parameters, material properties, and sensor grid configuration. The geometric input comprised of the six variable design parameters defined in Table 2. These parameters were dynamically modified by the Genetic Algorithm to generate different building geometries for each design alternative. Other geometric and simulation conditions that were not included as optimization variables were maintained consistently throughout the simulation process.

The second major input group comprised the optical properties of the building materials, including the floor, walls, ceiling, shading devices, and glazing. These material properties were not included as optimization variables and were therefore kept constant across all design alternatives. The materials were assigned using the built-in material properties provided by ClimateStudio. The material configuration used in this study employed a reflectance value of 0.425 and a transmittance value of 0.47 for the glazing material. By maintaining constant material properties, the simulation isolated the effects of the six geometric optimization parameters on daylighting performance rather than introducing variations caused by changes in material properties.

The third major input group was the sensor grid used to evaluate daylighting performance. The sensor grid was defined as a planar simulation surface positioned 0.7 m above the finished floor, with a consistent spacing of 3 meters between adjacent measurement points. Although the grid spacing remained fixed, the total number of measurement points varied across the optimization process. As the building floor area changed according to the geometric optimization parameters, the number and spatial distribution of sensor points were automatically adjusted to correspond to the geometry of each generated design alternative. Consequently, each simulation could contain a different number of measurement points while maintaining the same 3-meter spacing between adjacent points. This study selected $UDI_{100–3000}$ as the primary performance indicator because of its more comprehensive ability to evaluate indoor environmental quality compared to other metrics (Lou et al., 2025). This study adopted the refined UDI classification based on the 100–3000 lux useful daylight range. Within this classification, illuminance below 100 lux is categorized as underlit, 100–300 lux as UDI-supplementary, 300–3000 lux as UDI-autonomous, and above 3000 lux as over lit. For the optimization process, the combined 100–3000 lux range ($UDI_{100–3000}$) was used as the primary daylighting performance metric (Mardaljevic et al., 2017). ClimateStudio calculated the annual $UDI_{100–3000}$ value at each individual measurement point using the 100–3000 lux illuminance range. For the optimization process, however, the $UDI_{100–3000}$ value of a single measurement point was not directly used as the fitness value. Instead, the $UDI_{100–3000}$ values from all measurement points within each generated design alternative were spatially averaged to obtain a single $UDI_{100–3000}$ value representing the overall daylighting performance of the evaluated space. This spatially averaged $UDI_{100–3000}$ value was subsequently used as the fitness value to be maximized by the Genetic Algorithm.

The optimization process was carried out using Galapagos, which provides two optimization solvers: the Evolutionary Solver and the Annealing Solver. In this study, the Galapagos Evolutionary Solver was selected to perform the Genetic Algorithm approach. Each design alternative was represented as a genome in which the design variables defined in Table 2 constituted the genes. The combination of values assigned to these six genes formed a single design configuration, which was subsequently evaluated using CBDM simulation.

A collection of genomes formed a population that was evaluated during each optimization generation. The optimization process employed the Galapagos Evolutionary Solver with a population size of 50 individuals per generation. The population size determines the number of individuals evaluated in each regular generation. A population size of 50 was adopted for this study as the selected configuration for the optimization process. This value was not based on a specific statistical requirement or a universally prescribed population size, as the appropriate population size may vary depending on the optimization problem and computational requirements.

To increase solution diversity during the early stage of optimization, an initial boost factor of 2 was applied, resulting in a first-generation population that was twice the size of the standard population. Thus, the initial generation consisted of 100 individuals (50 × 2), while subsequent generations contained 50 individuals. In addition, the optimization utilized an elitism rate (maintain) of 5% to preserve the best-performing individuals in each generation and an inbreeding rate of 75% to guide the evolutionary process toward regions of the solution space with higher performance. These settings represent the Galapagos solver configuration adopted in this study for genetic algorithm optimization. (Turrin et al., 2011). The Genetic Algorithm configuration employed in this study is presented in Table 3.

Table 3. Genetic Algorithm Configuration

Parameter	Population Size	Initial Boost	Elitism Rate (Maintain)	Inbreeding Rate	Number of Generations	Total Design Evaluations
value	50	2	5%	75%	18	950

The $UDI_{100–3000}$ average values obtained from the simulations were used as fitness values to assess the quality of each genome. Genomes with higher fitness values had a greater probability of being retained and producing offspring in subsequent generations. Through the processes of selection, crossover, and mutation, the Genetic Algorithm generated new solution variations, enabling continuous exploration of the design space.

In addition to fitness values, this study also utilized the biodiversity indicator generated by Galapagos to monitor the level of solution diversity across generations. Biodiversity represents the degree of variation among genomes within a population. A high biodiversity value indicates that the population still consists of diverse solutions, whereas a decline in biodiversity suggests that the population is beginning to cluster around specific regions of the solution space associated with superior performance.

During the early generations, the population exhibited high biodiversity because it consisted of a wide range of design parameter combinations. As the evolutionary process progressed, high-performing genomes gradually became dominant within the population, leading to a reduction in biodiversity and causing the population to converge toward particular regions of the solution space. This condition indicated the occurrence of convergence, a process in which optimization increasingly focuses on parameter combinations that consistently produce better daylighting performance than alternative solutions.

The optimization process generated 950 design evaluations across 18 evolutionary generations. The first generation consisted of 100 individuals due to the initial boost factor of 2, while the subsequent 17 generations consisted of 50 individuals each, resulting in a total of 950 evaluated designs. The analysis focused on both the optimum solution generated by the optimization process and the convergence patterns that emerged throughout the evolutionary process. In addition to identifying the design configuration with the highest $UDI_{100–3000}$ average value, the study also examined the distribution of gene values within the final population to identify parameter ranges that were consistently associated with high daylighting performance.

RESULTS AND DISCUSSION

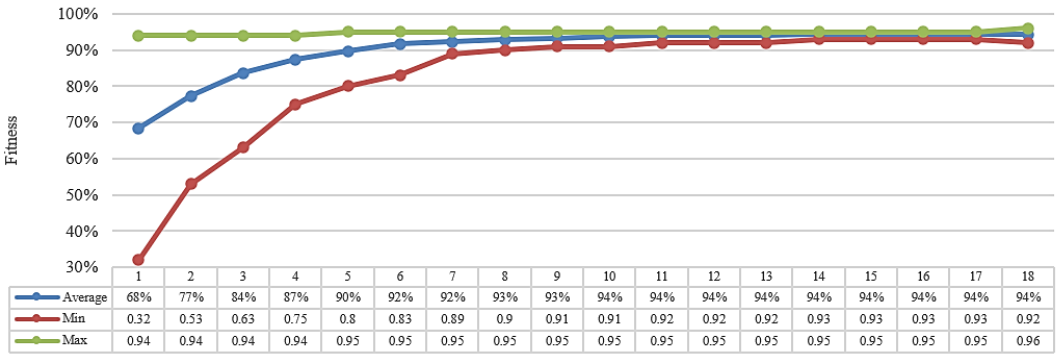
The results of this study were obtained through an optimization process using a PDGD approach that integrates parametric modelling, CBDM simulation, and a Genetic Algorithm. The optimization process successfully evaluated a total of 950 design alternatives using $UDI_{100–3000}$ average value as the objective function. This section discusses the progression of the optimization process, the optimum design configuration obtained, the convergence trends of design parameters throughout the evolutionary process, and the implications of the findings for office building design in the Tangerang Aerotropolis area.

Evolution of Optimization Process

The optimization process was conducted over 18 generations and produced a total of 950 design evaluations. Each generation consisted of a population of individuals representing different combinations of design parameters, which were evaluated based on the $UDI_{100–3000}$ average values obtained from CBDM simulations. The progression of fitness values throughout the optimization process is presented in Figure 6.

As shown in Figure 6, the fitness values exhibited an increasing trend from the initial generations to the final generations. The figure presents the minimum, average, and maximum fitness values obtained from all design alternatives evaluated within each generation. The fitness values are expressed as percentages and represent the spatially averaged $UDI_{100–3000}$ calculated from all measurement points within each generated design alternative. In the first generation, the initial boost factor of 2 resulted in 100 evaluated design alternatives, from which the

minimum, average, and maximum fitness values were 32%, 68%, and 94%, respectively. From the second to the eighteenth generation, each generation consisted of 50 evaluated design alternatives. As optimization progressed, the minimum and average fitness values increased substantially, while the maximum fitness values remained relatively high and gradually improved from 94% to 96%. This trend indicates that the evolutionary process progressively shifted the population toward design configurations with higher overall daylighting performance.

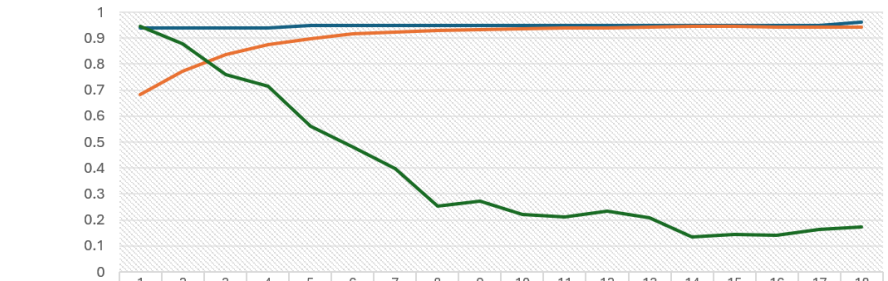


	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Average	68%	77%	84%	87%	90%	92%	92%	93%	93%	94%	94%	94%	94%	94%	94%	94%	94%	94%
Min	0.32	0.53	0.63	0.75	0.8	0.83	0.89	0.9	0.91	0.91	0.92	0.92	0.92	0.93	0.93	0.93	0.93	0.92
Max	0.94	0.94	0.94	0.94	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.96

Fig 6. Fitness Evolution

The increasing minimum fitness value is particularly indicative of convergence because it shows that even the lower-performing alternatives within each generation gradually approached the performance level of the better-performing solutions. The reduction in the gap between the minimum, average, and maximum fitness values from the early to the later generations indicates that the population became increasingly concentrated around high-performing regions of the solution space. By Generation 18, the fitness values ranged from 92% to 96%, with an average of 94%, indicating a substantially more homogeneous population of high-performing design alternatives compared with the first generation.

In addition to the evolution of fitness values, the optimization process also revealed changes in population diversity, referred to as biodiversity. Figure 7 presents the relationship between the fitness performance and biodiversity of the population across the 18 generations. The $UDI_{100–3000}$ values shown in the figure do not represent the $UDI_{100–3000}$ of a specific sensor or a single design solution. Instead, they correspond to the minimum, average, and maximum spatially averaged $UDI_{100–3000}$ values obtained from all design alternatives evaluated within each generation, as presented in Figure 6. Each $UDI_{100–3000}$ value represents the spatial average of the $UDI_{100–3000}$ values calculated across all measurement points within an individual design alternative.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
UDI	0.94	0.94	0.94	0.94	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.96
Avg UDI	0.6839	0.7728	0.837	0.8742	0.8974	0.9172	0.9232	0.9286	0.9326	0.9374	0.9394	0.94	0.9414	0.944	0.9446	0.9432	0.9434	0.9428
Biodiversity	0.947	0.877	0.759	0.715	0.562	0.48	0.397	0.254	0.272	0.22	0.212	0.233	0.21	0.135	0.143	0.141	0.163	0.172

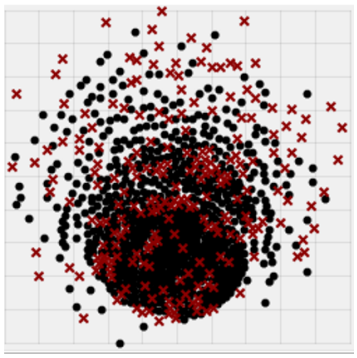


Fig 7. Biodiversity Evolution

The first generation consisted of 100 design alternatives due to the initial boost factor of 2, whereas Generations 2–18 each consisted of 50 alternatives. As shown in Figure 7, the maximum and average $UDI_{100–3000}$ values remained relatively high throughout the optimization process, while the minimum $UDI_{100–3000}$ value increased substantially from the early to the later generations. At the same time, biodiversity decreased from 0.947 in the first generation to approximately 0.172 in the final generation. This simultaneous reduction in biodiversity and increase in the minimum $UDI_{100–3000}$ indicates that the population progressively became more concentrated around high-performing regions of the design space. In other words, the evolutionary process did not only maintain high-performing solutions but also progressively reduced the presence of low-performing solutions within the population.

The relationship between the two indicators provides evidence of convergence. While Figure 6 illustrates the progression of the minimum, average, and maximum fitness values of each generation, Figure 7 further shows that

the improvement in the lower-performing solutions was accompanied by a reduction in population diversity. This indicates that the optimization progressively narrowed the explored solution space toward design configurations associated with higher daylighting performance. The decline in biodiversity accompanied by an increase in fitness is a common characteristic of Genetic Algorithm-based optimization, in which higher-performing individuals tend to dominate the gene pool and produce offspring in subsequent generations (Maleki & Dehghan, 2020). The combination of these two indicators demonstrated that the resulting solution was not obtained through a random search process but rather through a stable and directed evolutionary process that ultimately reached convergence in the final generations.

Optimum Design Solution

The optimization process produced a maximum $UDI_{100–3000}$ average value within the range of 95.50% to 96.00%, indicating that nearly the entire internal workspace remained within the illuminance range considered ideal for occupant visual activities throughout annual operating hours. The single best-performing design configuration is presented in Table 4.

Table 4. Optimum Design Configuration

Parameter	WWR	Window Height	Shading Spacing	Shading Depth	Building Width	Orientation	$UDI_{100–3000}$
Value	0.47	2.53 m	0.40 m	0.40 m	12.0 m	76°	95.50%

Figure 8 illustrates the geometric configuration of the optimum solution generated by the optimization process. This combination of design parameters produced a daylight distribution that satisfied the $UDI_{100–3000}$ criteria across most of the occupied floor area. The simulation results are visualized in Figure 9 to demonstrate the distribution of daylighting performance for the optimum configuration throughout each month of the year.

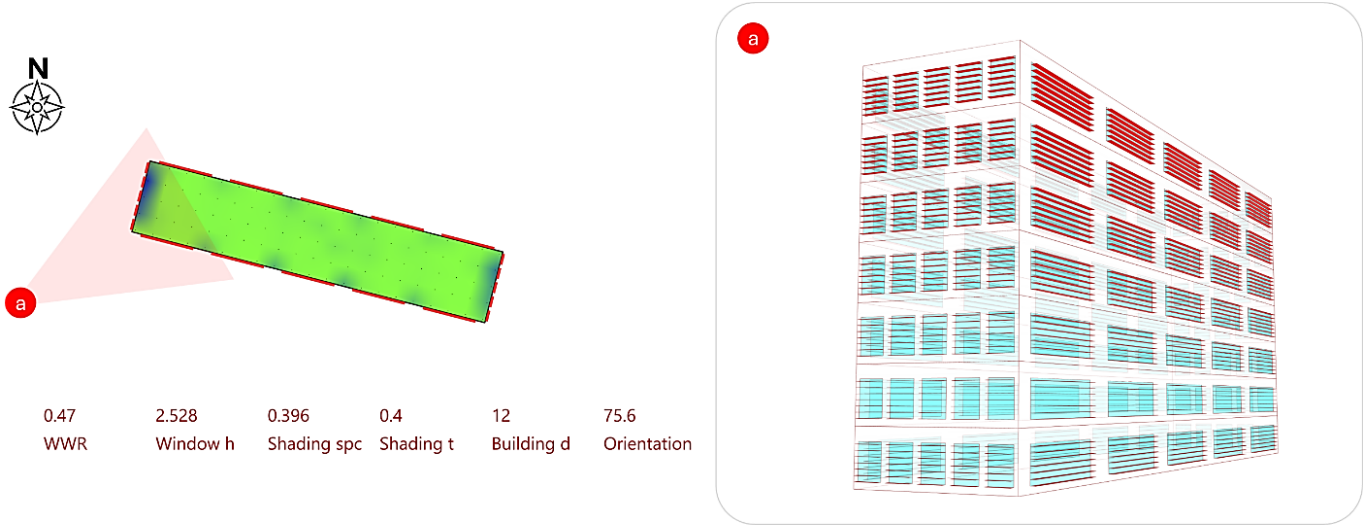


Fig 8. Optimum Building Configuration

The optimization results indicated that high daylighting performance was achieved through the simultaneous interaction of multiple design parameters rather than through the modification of any single parameter in isolation. The optimum configuration represented a precise trade-off among window size, the geometric characteristics of shading devices, building mass proportions, and building orientation relative to the solar path.

The most sensitive and influential parameter was building width, which reached the lower bound of the optimization domain at 12.00 m. This result demonstrated that building width has the most significant impact on daylight penetration into interior spaces. A shallow floor plate reduces the distance that daylight must travel, allowing sky components to penetrate deeper into the building from both façades and substantially increasing Useful Daylight availability (Alsukkar et al., 2026).

Building orientation also exhibited a strong preference, converging toward a value of 76°. This result suggested that rotating the building along this axis is highly effective in reducing direct solar exposure from the east–west direction on large façade surfaces while simultaneously promoting the distribution of diffuse daylight throughout the year.

Interestingly, the optimum WWR reached a relatively high value of 0.47. Despite the large window area, excessive daylight exposure (over lit conditions) was avoided through the effective compensation provided by a dense horizontal shading configuration, characterized by a shading spacing of 0.40 m and a shading depth of 0.40 m. This finding confirms that daylighting performance is not governed by the restriction of a single design parameter but rather by the integrated interaction of multiple parameters that collectively offset the limitations of one another (Sultana & Rahman Joarder, 2025).

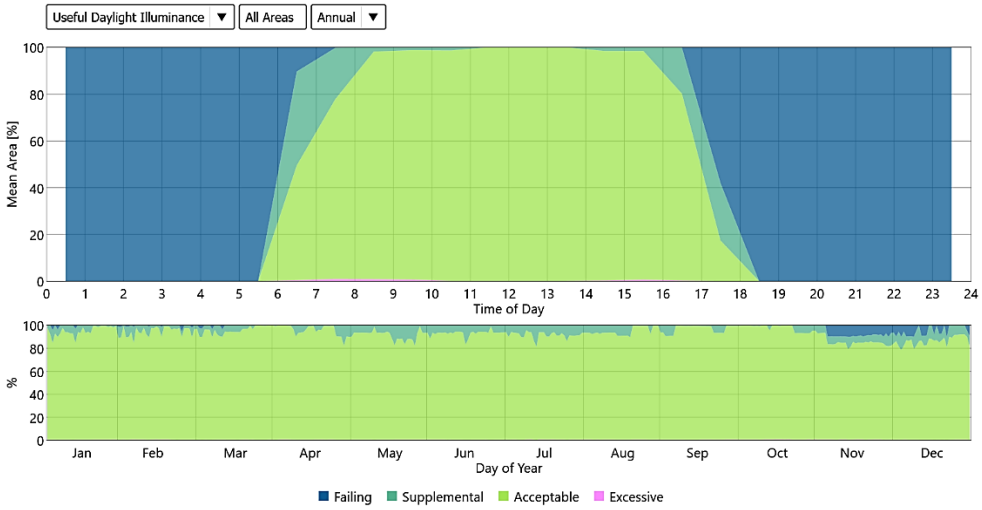


Fig 9. $UDI_{100–3000}$ Simulation Result of Optimum Design

Convergence of Design Parameters

In addition to identifying a single optimum solution, the optimization process was analyzed by tracking the best-performing design configuration in each generation. As shown in Figure 10, each generation produced one best-performing genome consisting of a complete combination of the design parameters. The parameter values of the best-performing genome were recorded for each generation from Generation 1 to Generation 18. These generation-specific best-performing solutions provide multiple high-performing design configurations that emerged throughout the optimization process. The convergence range presented in Table 5 was then derived from the minimum and maximum values of each parameter across these 18 generation-specific best-performing solutions. Therefore, the six parameter values within each generation were retained as one complete design configuration and were not combined independently across generations.

Table 5. Convergence Range of High-Performance Design Solutions

Parameter	Window-to-Wall Ratio (WWR)	Window Height (m)	Shading Spacing (m)	Shading Depth (m)	Building Width (m)	Building Orientation (°)
Convergence Range	0.40–0.47	2.50–2.60	0.30–0.50	0.30–0.40	12–13	72–84

Figure 10 illustrates the evolution of the design variables corresponding to the best-performing genome in each generation. The horizontal axis represents the generation number, while each value represents the corresponding parameter value of that generation's best-performing design. The six parameter values within the same generation constitute one complete design configuration. The progressive stabilization of these values across generations provides the basis for the convergence ranges summarized in Table 5.

Following the analysis of fitness, biodiversity, and parameter convergence, the morphological evolution of the best-performing design configurations was examined. As shown in Figure 11, each configuration represents the complete combination of the design variables of the best-performing genome identified in the corresponding generation, as shown in Figure 10. The figure therefore provides a visual representation of how the geometric and façade characteristics of the best-performing solutions changed across the 18 generations. The morphological variation observed in the early generations gradually became more consistent in the later generations, corresponding to the stabilization of the parameter values and the convergence ranges presented in Table 5. This morphological stabilization indicates that the Genetic Algorithm progressively narrowed the design search toward a smaller range of high-performing daylight-responsive configurations.

Based on the comparative statistical analysis, each variable exhibited a different level of contribution and convergence strength. WWR tended to converge within the upper-middle range (0.40–0.47), while window height

clustered tightly between 2.50 and 2.60 m. This pattern suggests a non-linear relationship in which increasing window area beyond this range may reduce daylighting performance due to excessive overlit conditions. Similarly, shading spacing and shading depth converged within relatively narrow ranges, confirming the role of shading devices in regulating daylight intensity so that illuminance levels remain within the $UDI_{100–3000}$ comfort range.

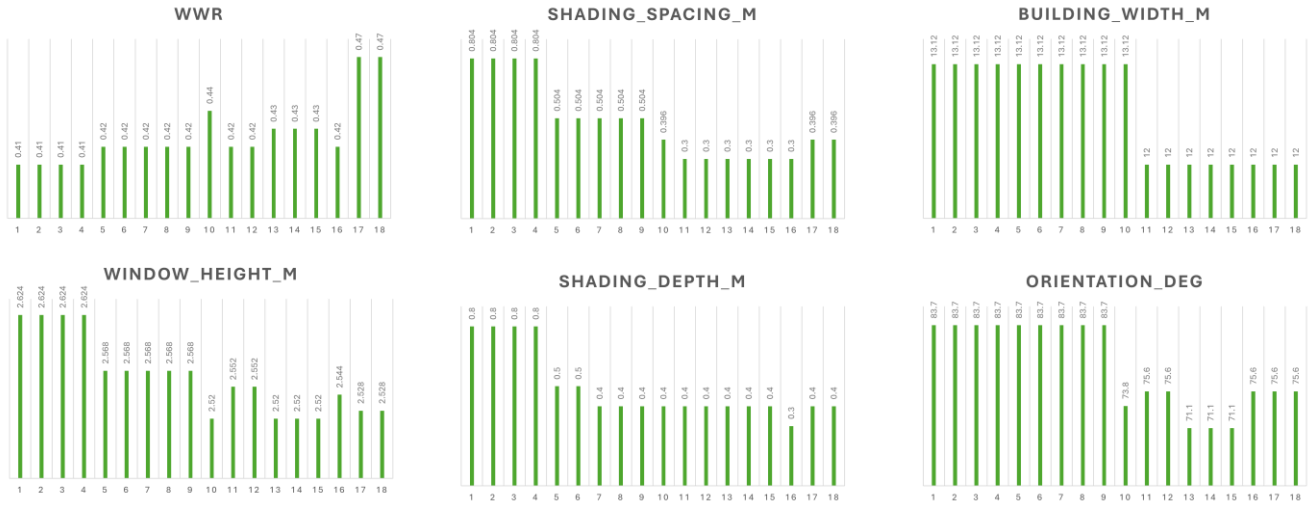


Fig 10. Distribution of High-Performance Design Solutions

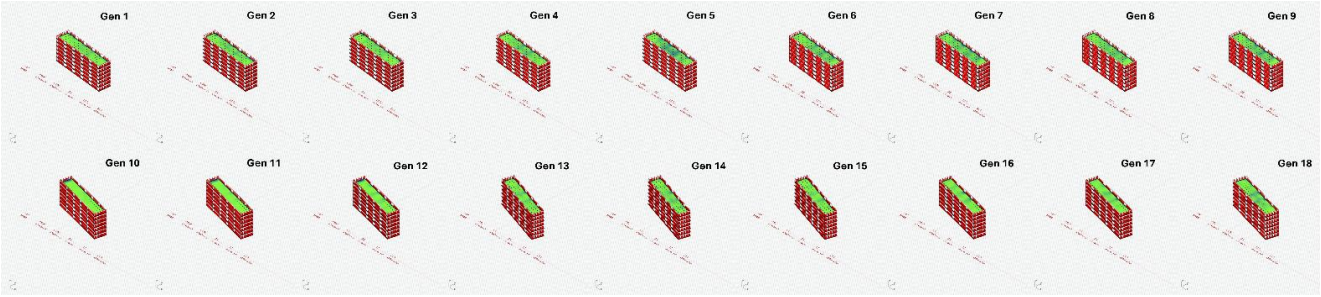


Fig 11. Evolution of Best Design Solutions Across Generations

The strongest and most homogeneous convergence occurred in the building width parameter (12.00–13.00 m). The consistent clustering of solutions near the lower boundary of the optimization domain indicates that floor plate depth is one of the most influential architectural variables affecting daylight distribution quality. In contrast, building orientation exhibited a slightly broader convergence range (72°–84°), suggesting that rotational flexibility within this interval can still achieve comparable levels of visual comfort performance.

These convergence patterns demonstrate that the generative optimization process does not merely produce a single fixed solution but successfully identifies a family of solutions that consistently achieve high performance. From a professional design perspective, identifying such design ranges provides greater practical value than a single optimum solution because it offers flexibility for architectural decision-making while maintaining building performance quality (SOMANATH, 2019). To summarize the behavior of each design variable, the interpretation of parameter convergence is presented in Table 6.

Table 6. Interpretation of Design Parameter Convergence

Parameter	***Observed Trend***	***Design Interpretation***
WWR	Moderate convergence around 0.40–0.47	Moderate façade openness provides sufficient daylight while avoiding excessive illuminance.
Window Height	Concentrated around 2.50–2.60 m	Intermediate window height improves daylight penetration without excessive exposure.
Shading Spacing	Converged toward smaller spacing values	Closely spaced shading devices help maintain illuminance within the $UDI_{100–3000}$ range.
Shading Depth	Converged around 0.30–0.40 m	Moderate shading depth balances daylight admission and glare reduction.
Building Width	Strong convergence at 12–13 m	Shallower floor plates enable deeper daylight penetration.
Building Orientation	Concentrated around 72–84°	Orientation significantly affects annual daylight distribution.

The parameter convergence results indicate that each variable contributes differently to daylighting performance. As shown in Table 6, the Window-to-Wall Ratio converged within a moderate range, suggesting that increasing window area does not necessarily lead to a linear improvement in daylighting performance. Meanwhile, shading spacing and shading depth clustered within relatively narrow intervals, indicating that shading devices play an important role in maintaining illuminance levels within the $UDI_{100–3000}$ range. The strongest convergence occurred in building width, highlighting that floor plate depth is one of the most influential factors affecting daylight penetration. Building orientation also demonstrated convergence within a specific range, emphasizing its importance in controlling daylight distribution throughout the year.

Design Implications and Application to the Tangerang Aerotropolis Area

The results of this study demonstrate that the PDGD approach can identify the relationships among multiple design parameters that influence daylighting performance. The main findings indicate that relatively shallow building configurations, building orientations approaching the east–west axis, and specific shading device configurations produce higher daylighting performance than alternative design solutions.

Within the context of the Tangerang Aerotropolis area, where vertical development is constrained by Airport Operational Safety Zone regulations, the optimization of building massing and envelope configurations represents a relevant strategy for improving indoor environmental quality. The findings indicate that design decisions related to building orientation, mass proportions, and shading configurations have significant effects on daylighting performance.

This study also demonstrates that a multi-parameter optimization approach produces insights that differ from those obtained through single-parameter evaluations. For example, the relatively high optimum Window-to-Wall Ratio can only be properly understood when considered in conjunction with other design parameters, including building orientation, building width, and shading configuration. This finding highlights that daylighting performance results from the interaction of multiple parameters operating simultaneously rather than from the effect of any single parameter in isolation.

Overall, the results indicate that the PDGD approach is capable of generating optimum solutions as well as revealing patterns and tendencies among design parameters associated with high performance. These patterns can provide an initial design reference for office buildings in the Tangerang Aerotropolis area. However, the optimum configuration identified in this study should not be regarded as a fixed solution for all buildings in the region, since the optimization was conducted using a specific building model and defined boundary conditions.

The simulation was conducted under the assumption of no external shading from surrounding buildings. Therefore, inter-building shading effects were not considered in the daylighting assessment.

CONCLUSION

This study successfully applied a PDGD approach to optimize daylighting performance in office buildings within the Tangerang Aerotropolis area through the integration of Rhinoceros 3D, Grasshopper, ClimateStudio, and Galapagos. The optimization process effectively evaluated a total of 950 design alternatives generated over 18 evolutionary generations using $UDI_{100–3000}$ average value as the objective function.

The results indicate that the best design configuration achieved an exceptionally high $UDI_{100–3000}$ average value of 95.5%. This level of performance was attained through a specific combination of architectural parameters: a Window-to-Wall Ratio (WWR) of 0.47, a window height of 2.53 m, a horizontal shading spacing of 0.40 m, a horizontal shading depth of 0.40 m, a building width of 12 m, and a building orientation of 76°. These findings provide empirical evidence that achieving high levels of visual comfort in tropical climates is the result of simultaneous interactions among multiple design parameters rather than the manipulation of a single variable.

The population convergence analysis identified a set of safe design ranges in which high-performing solutions consistently clustered. These ranges include a WWR of 0.40–0.47, a window height of 2.50–2.60 m, a horizontal shading spacing of 0.30–0.50 m, a horizontal shading depth of 0.30–0.40 m, a building width of 12–13 m, and a building orientation of 72°–84°. Among all variables, building width and shading configuration demonstrated the strongest sensitivity to achieving high $UDI_{100–3000}$ performance.

From a practical perspective, this study provides an initial design reference for architectural development within the Tangerang Aerotropolis area, where vertical development is constrained by Airport Operational Safety Zone (KKOP) regulations. When vertical expansion is limited, the findings suggest that subdividing building mass into shallow floor plates (12–13 m) combined with closely spaced parametric shading devices can serve as an effective strategy for preventing underlit conditions while minimizing the risk of excessive daylight exposure.

Future research may extend this approach through multi-objective optimization by simultaneously integrating daylighting performance ($UDI_{100–3000}$), total energy consumption (Energy Use Intensity), indoor thermal comfort (PMV/SET), and dynamic glare potential (Daylight Glare Probability). Such an approach would enable the generative system to produce more comprehensive and holistic design recommendations for commercial architecture in tropical climates.

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DECLARATIONS

Declaration of AI Use

AI-assisted technology was used during the preparation of this manuscript for language editing and proofreading. The authors remain fully responsible for the content, accuracy, originality, integrity, and proper attribution of the manuscript.

Author Contributions

S.Y. contributed to the conceptualization, methodology, software development, investigation, formal analysis, data curation, visualization, and preparation and revision of the manuscript. M.L.P. contributed to the conceptualization of the study, particularly in defining the architectural element and building-envelope configuration used as the case study, as well as to the review and editing of the manuscript. L.A.M. contributed to the investigation, particularly to the selection of the study location, and to the review and editing of the manuscript. All authors have read and agreed to the published version of the manuscript.

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Conflict of Interest

The authors declare no conflict of interest.

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