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Multi-Objective Optimization of Daylighting–Thermal Performance in Cold-Region University Library Atriums: A Parametric Design Approach

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Abstract: Open atrium spaces in university libraries have emerged as a prevalent architectural trend. While increasing daylighting through enlarged glazing areas enhances the indoor environment, it simultaneously introduces significant thermal challenges in cold regions where environmental comfort demands lead to higher energy loads. This study investigates the optimization of daylighting–thermal performance balance through a multi-objective parametric approach to address the inherent conflicts between environmental quality and energy efficiency in atrium design. In this paper, we take the library project in the cold region as a practical case, use the measured data to support the simulation experiment, combine the parametric platform and multi-objective coupling optimization algorithm to carry out digital modeling, and explore the dynamic relationship between the atrium light, heat environment, and the value of energy consumption under the influence of a variety of parameters. The experimental results show that the quality and energy efficiency of the atrium light environment are improved after parameter optimization. The energy consumption per unit area (EUI) is reduced by 84.84 kwh/m^2–106.83 kwh/m^2 while the adequate natural illuminance (UDI) is increased by 5.06–27.64%, which confirms the feasibility of the research and development of the building light–heat coupling optimization technology route and program module. This paper aims to explore the quantitative law of design elements on light–heat balance at the early stage of architectural design and to provide a theoretical basis and reference blueprint for improving the comprehensive decision-making ability of architects in sustainable design and realizing integrated and efficient program decision-making.

Keywords: cold regions; atrium space; light–heat balance; energy efficiency improvement; parametric techniques; multi-objective coupled optimization

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1. Introduction

The global energy crisis and environmental challenges have brought unprecedented attention to building energy efficiency. According to the China Building Energy Consumption Research Report (2020), the total energy consumption of public buildings in China accounted for 38.3% of the total national energy consumption in 2018 [1]. Public buildings with atrium spaces in cold regions face particular challenges regarding energy efficiency, with heating systems contributing significantly to their overall energy consumption [2]. Libraries, as essential public buildings, demonstrate concerning energy consumption patterns, with heating and air conditioning accounting for 40–60% of total energy usage and lighting consuming an additional 20–30% [3]. Implementing large-scale central air-conditioning systems, necessary for optimal environmental conditions, further exacerbates these energy consumption challenges.

The integration of open atrium spaces in contemporary library design has become increasingly prevalent, driven by demands for collaborative learning environments [4]. This architectural approach presents a dual challenge: while enhanced daylighting through increased glazing areas improves spatial quality, it simultaneously introduces substantial thermal management issues. In cold-region buildings, where stable thermal conditions are crucial, HVAC and lighting systems can account for over 70% of the total energy consumption. The requirement for stable thermal conditions in these spaces necessitates careful consideration of the balance between daylighting performance and energy efficiency during the initial design phase [5]. The requirement for stable thermal conditions in these spaces results in air conditioning and lighting accounting for more than 70% of the total energy consumption, highlighting the critical need for optimizing light–heat balance during the initial design phase [6].

Traditionally, architects have relied heavily on empirical knowledge for energy-saving design decisions, leading to suboptimal outcomes in achieving sustainable design goals and balancing lighting requirements with energy efficiency [7]. The limitations of conventional design methodologies have been particularly evident in addressing the complex interplay between natural lighting and thermal performance [8]. Recent advances in parametric simulation technology have emerged as a promising solution to overcome these traditional design constraints [9,10]. These technological innovations enable coupled simulation and automatic optimization through genetic algorithms, providing a more sophisticated approach to energy consumption and lighting optimization [11].

Recent research has made significant strides in this direction. Studies have utilized comprehensive performance evaluation models to investigate the impact of curtain wall configurations on cost, energy consumption, and the light–thermal environment [12]. Furthermore, researchers have developed performance-optimized design frameworks and energy consumption-lighting optimization models to explore strategies for reducing energy intensity while enhancing daylighting performance during early design stages [13]. However, existing studies on library atrium light–heat balance have predominantly focused on program selection [14], with a limited investigation into systematic pattern changes, resulting in efficiency limitations and insufficient solution accuracy [15].

The evolution of building information modeling (BIM) and environmental simulation tools has created new opportunities for integrating energy performance analysis into the early design process [16]. Recent studies have demonstrated the potential of machine learning algorithms in optimizing building envelope design for energy efficiency [17]. Additionally, research has shown that proper daylighting strategies can reduce artificial lighting energy consumption by up to 60% while maintaining visual comfort [18]. Developing advanced glazing technologies and innovative building materials has further expanded the possibilities for achieving optimal light–heat balance [19,20].

This research addresses these challenges by enabling architects to maximize energy efficiency while balancing various performance aspects during the early stages of building design. We aim to guide building design through quantitative analysis and propose multi-objective optimization strategies. Using a university library in a cold region as a case study, we seek to optimize building performance across multiple parameters and establish appropriate value ranges for atrium design parameters in cold regions.

2. Theoretical Modeling

There exists an intricate relationship between energy consumption and two key building performance metrics: daylighting performance and thermal environment. In core atrium design with skylight systems, this relationship manifests in two primary ways. First, insufficient skylight area necessitates increased artificial lighting, leading to higher lighting energy consumption. Second, excessive glazing area can cause visual discomfort through glare while simultaneously increasing heat exchange, resulting in elevated HVAC energy consumption. The optimization of these competing factors forms the central challenge in atrium design, particularly in cold regions where thermal performance is critical. Therefore, this paper, by constructing theoretical models and developing program modules for optimization of light and heat coupling in buildings, is committed to seeking solutions that meet the requirements of high-efficiency natural lighting, highly satisfactory thermal environment, and low energy consumption, guiding the practice of architectural design and further bringing into play the dynamics of architectural design, which is the key point of the research on coupling objectives.

2.1. Evaluation Standard of Light and Heat Environment

The evaluation index of indoor light environment is mainly divided into two categories: static and dynamic; through the comparative analysis of the light environment evaluation index, the year-round dynamic evaluation index can fully take into account the change rule of the year-round solar operation and the year-round weather conditions, the evaluation of the year-round atrium indoor lighting is more comprehensive, which is conducive to the study of the atrium in the energy-saving potential of lighting energy consumption. Studies have shown that natural lighting illuminance higher than 2000 lx causes glare, so our eyes will be obviously uncomfortable, and lower than 300 lx when we complete the visual work will be difficult. At the same time, due to the high dimensionality of the area where the study is located, there is a large difference in climate between summer and winter. We compared the natural daylighting data in summer and winter. It can be found that, in the summer atrium at noon, there are more test points with illuminance above 2000 lux in the test plane, which indicates that the design of preventing dazzling should be fully considered in the summer. In winter, the average length of time that the lighting point is greater than 300 lux in the atrium test plane without artificial supplemental lighting is only 6.4 h. This shows that the atrium lighting design in winter should focus on balancing the lighting energy consumption and natural lighting design. At the same time, in order to balance the design indexes throughout the year, we refer to the local design codes and limit the indexes used for evaluating the lighting capacity of the atrium to between 300 and 2000 lux, in order to balance the dazzling light and lighting design. We compared the current light standards in China and Europe, and the illumination requirements for spaces with different usage functions vary as follows (Table 1). In the table, we can find that the optimal illuminance of the desktop for reading is between 300 and 500 lux, while the illuminance of different areas of the library ranges from 300 to 1000. The research object of this paper is to take into account the reading and corridor function of the open space, while taking into account the function of preventing glare, so the illuminance evaluation range is limited to 300–2000 lux. In this paper, we study the comfort of the lighting environment of the atrium and consider the natural lighting illuminance and glare; so, we chose UDI300 lx < E < 2000 lx to evaluate the lighting performance and the index of lighting optimization throughout the year.

Table 1. Recommended illuminance standards for different building spaces.

Illuminance Range (lux)	Applicable Scene/Function	Remarks
100–200	Warehouses, hospital wards, parking lots, general corridors, rest areas	Suitable for low-activity areas where basic visibility is sufficient
200–300	General offices, restaurants, general classroom lighting	Provides comfortable basic lighting
300–500	Meeting rooms, supermarkets, shops, general classrooms, study rooms	Suitable for general reading, writing, and product display
500–750	Reading areas, drawing areas, blackboard lighting, precision office work, laboratories	Suitable for tasks requiring higher visual clarity
750–1000	Fine handcrafting, precision assembly, library search areas, high-intensity sports areas	Higher brightness needed to reduce eye strain and improve accuracy
1000–2000	Operating rooms, jewelry making, electronics repair, design drafting, embroidery	Suitable for high-precision visual tasks, ensuring clear details

Domestic and international evaluations of the thermal environment of the atrium evaluation indexes include temperature value, temperature distribution, thermal comfort, solar radiation heat gain, air conditioning energy consumption (heating energy consumption and cooling energy consumption sum), and so on. In this open-plan library reading space, we aim to balance natural lighting comfort and thermal comfort. The comfortable temperature range in a standard library reading room is generally determined based on human comfort, air circulation, and energy efficiency standards, typically between 20 °C and 26 °C. Since this study focuses on an open atrium space, increasing the winter design temperature by just 1 °C will result in a 13% increase in energy consumption. Therefore, considering regional standards and energy-saving requirements, we have reasonably optimized the heating and cooling threshold standards for winter and summer to achieve a balance between comfort and energy consumption. The air conditioning temperature is set at 18~22 °C in winter and 24~28 °C in summer to reach a comfortable temperature in civil buildings [21], so this paper selects the air conditioning energy consumption under the premise of ensuring the comfortable temperature value of the atrium as the evaluation index of the thermal environment.

2.2. Energy Consumption Evaluation Standard

Since the indicators of the light environment and the indicators of the thermal environment discuss different dimensions, there is a lack of comparability between them, which is not conducive to the discussion of the balance between the light environment and the thermal environment. Therefore, this paper chooses to quantify the evaluation objectives of the light and heat dimensions into energy consumption indicators, i.e., the corresponding lighting energy consumption and cooling and heating energy consumption (air conditioning energy consumption) for discussion. The energy consumption per unit area of a building can be characterized by the sum of the lighting energy consumption, air conditioning energy consumption, and equipment energy consumption of the building, as shown in Equation (1). Therefore, the energy consumption per unit area (EUI) throughout the year is used as the evaluation index of energy consumption.

$$\begin{gathered}\mathrm{EUI} = \mathrm{E_l} + \mathrm{E_h} + \mathrm{E_c} + \mathrm{E_e} \\ \mathrm{E_l} = \frac{\mathrm{Q_l}}{\mathrm{A}}\ \mathrm{E_h} = \frac{\mathrm{Q_h}}{\mathrm{A}}\ \mathrm{E_c} = \frac{\mathrm{Q_c}}{\mathrm{A}}\ \mathrm{E_e} = \frac{\mathrm{Q_e}}{\mathrm{A}}\end{gathered} \tag{1}$$

Format:

EUI is the annual unit area energy consumption (kWh/m^2), A is the total area of the building (m^2)

E_l is the annual energy consumption of lighting per unit area (kWh/m^2), Q_l is the annual cumulative energy consumption of lighting (kWh)

E_h is the annual heating energy consumption per unit area (kWh/m^2), Q_h is the annual cumulative heating capacity (kWh)

E_c is the annual energy consumption for cooling per unit area (kWh/m^2), Q_c is the accumulated annual cooling capacity (kWh).

E_e is the annual energy consumption of equipment per unit area (kWh/m^2), Q_e is the annual cumulative energy consumption of equipment (kWh).

3. Parametric Simulation Experiment

In this paper, the benchmark model is constructed based on field research, and L+H in Grasshopper, a parametric plug-in for the Rhino platform, is used as the simulation tool for lighting, thermal environment, and energy consumption in this paper by invoking modules such as EnergyPlus, Radiance, Daysim, and OpenStudio. Moreover, the multi-objective coupled optimization operator Octopus is called and combined with a genetic algorithm and Pareto optimization principle for multi-objective coupled optimization experiments (Figure 1).

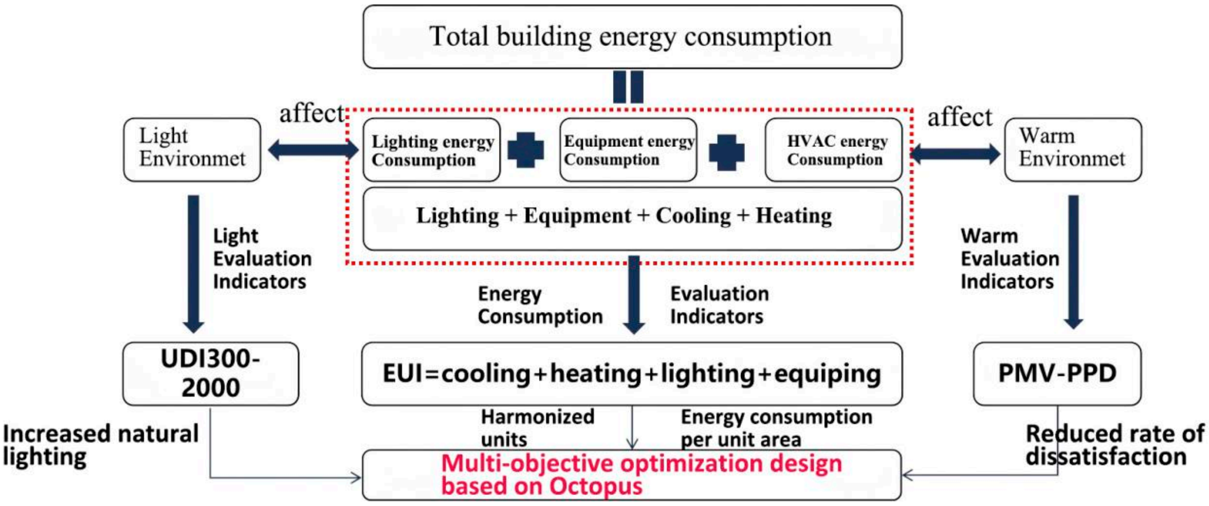


Figure 1. Evaluation model relationship diagram.

This research employs an integrated methodology comprising three main components:

(1) Benchmark Model Development:

Field research-based model construction
Validation through on-site measurements
Calibration with actual building performance data

(2) Parametric Environmental Analysis:

Implementation using Grasshopper for Rhinoceros
Environmental simulation through EnergyPlus (Version 9.5) for energy analysis
Daylighting calculation using Radiance (Version 5.2) and Daysim (Version 3.1)
Building information modeling integration via OpenStudio (Version 3.9.0)

(3) Multi-objective Optimization:

Deployment of Octopus optimization component
Implementation of genetic algorithms for parameter optimization

Application of Pareto optimization principles for multi-criteria decision making
Integration of performance metrics for comprehensive evaluation

3.1. Experimental Case

Shenyang, located at 41.8° N latitude in Liaoning Province, falls within the severely cold climate zone in China's building classification. According to the Köppen climate classification, it has a humid continental climate (Dwa), characterized by cold, dry winters influenced by Siberian air masses and hot, humid summers due to monsoonal effects. In the ASHRAE climate classification, it is categorized as Zone 6A (cold, humid), with significant heating demand in winter. These climatic conditions necessitate careful consideration of thermal comfort and energy efficiency in building design. Winter lasts from 1 November to 31 March of the following year, March–June is the transition season, and 1 June to 31 August is the summer in Shenyang. Based on the research results of the atrium of 48 university libraries in Shenyang City, it is found that the layout is mainly core type, the plane and profile shape are primarily rectangular, and top lighting is mainly adopted. Therefore, we select the moderate scale and representative atrium space of Northeastern University Ning Encheng Library as an example to build a benchmark model, analyze the current characteristics of the light and heat environment, and screen the impact of design elements.

3.1.1. Characteristics of the Current Light and Heat Environment in the Atrium of Ning Encheng Library of Northeastern University

In order to understand the current characteristics of the light and heat environment in the library, two days were selected on 13 and 22 June 2021, to conduct a survey (Figure 2), mainly monitoring the light and temperature in the atrium at the height of 0.75 m on the horizontal light test plane (the human body sitting position) as well as in the surrounding areas. After data collation and analysis, the 0.75 m high horizontal plane from the ground is subjected to more intense illumination of its illuminance value, the temperature value changes in a larger magnitude; from 8:00 to 12:00, the illuminance value continues to increase, the atrium temperature value also continues to rise; from 12:00 to 17:00, the illuminance value continues to decline and the atrium temperature value also continues to decrease. The illuminance value in the atrium is much higher than the standard value of 300 lux for most of the day. There is excessive light before and after, and the illuminance value is much higher than 2000 lux, which leads to an uncomfortable glare phenomenon. Due to the direct sunlight, the temperature in the atrium is higher than 26 °C, and, around noon, the temperature is as high as 32 °C, which exceeds the comfortable temperature in summer. Even with artificial light supplementation, there is still insufficient light in the peripheral area of the ground floor of the atrium. At the same time, there is also excessive glare on the top floor, which affects the regular use of the building. Therefore, there is room for optimizing the indoor light and heat environment. At the same time, we will conduct simulation modeling based on the building floor plan. There are no obstructions in the overall surrounding environment of the building, and the atrium space is enclosed on all four sides by reading and storage areas. During the modeling calculations, heat transfer and lighting calculations of the surrounding spaces have a minimal impact on the atrium area. Inside the atrium, there are multi-level open corridors, whose shape variations significantly affect natural lighting within the atrium. Therefore, the parameter design of these corridors will be a key focus for optimization in the simulation model.

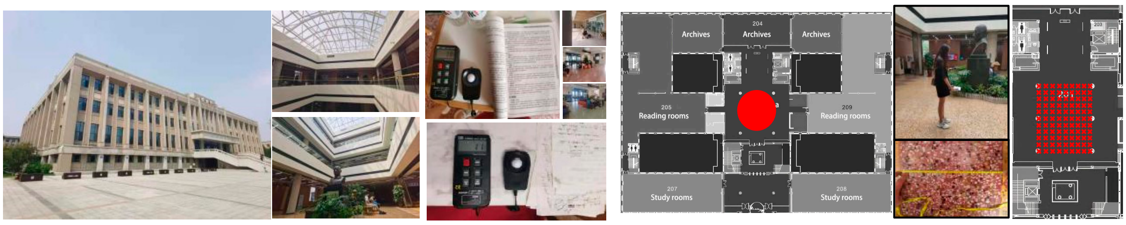


Figure 2. Field research at Ningencheng Library, Tohoku University.

3.1.2. Screening Influencing Design Factors

By generalizing and analyzing the influencing factors selected by researchers at home and abroad, it is summarized that the factors affecting the light and heat environment of the building atrium space mainly included space layout, space scale, and space interface. This paper selects the Ning Encheng Library of Northeastern University in Shenyang City as a practical case, i.e., the core atrium with a rectangular profile form. Therefore, the selected influencing factors mainly included space scale and interface. Under the premise that controlling other variables was unchanged, skylight area ratio (WWR), skylight spacing, atrium area share, and height were selected as the influencing variables of this study, respectively.

3.2. Simulation Experiment Parameter Design

3.2.1. Meteorological Parameter Setting

To ensure the establishment of the same thermal zone as the baseline model's plan layout, the study's validity and adaptability were improved. Meteorological data of Shenyang city were downloaded through EnergyPlus weather files (EPW) in Ladybug, and CSWD files of typical annual measured meteorological data were introduced into the parameterization platform (Figure 3).

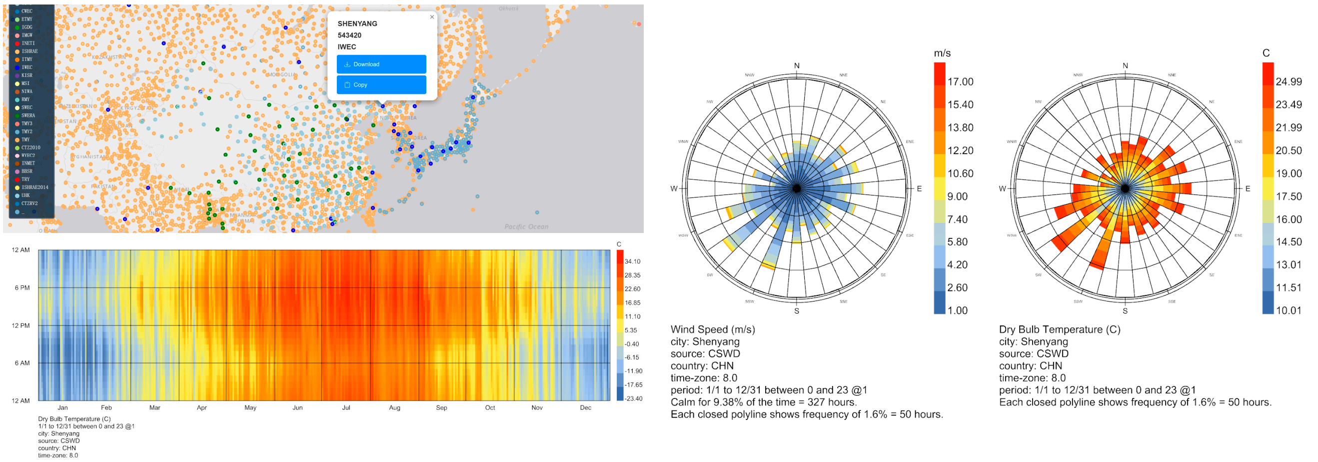


Figure 3. Visualization of climate data in Shenyang.

3.2.2. Light, Heat Environment, and Energy Consumption Simulation Parameter Settings

In order to meet the illuminance value of 300 lux for daily reading in the college library, the natural lighting simulation experiment in this paper needs to be adjusted to the minimum value of 300 lux, and its value range is 300~2000 lux. The light environment simulation experiment is the same as the physical test method: the height of the test plane is set to 0.75 m, and the spacing of each test point is 2 m. In order to achieve the real indoor natural lighting effect, the reflectivity of the roof, wall, floor, and glass [14] is set. In order to achieve the real indoor lighting effect, the reflectance of the roof, wall, floor, and glass [22] is set to be 0.8, 0.5, 0.2, and 0.6, respectively, concerning the "Architectural Lighting Design Manual" [23]. According to the previous analysis of the climate temperature characteristics of the Shenyang region, the summer temperature exceeds 26 °C to open the cooling equipment; the winter temperature is lower than 20 °C to open the heating equipment, and the transition season period relies on natural ventilation to regulate. The relevant parameters of the exterior wall, roof, and windows are set concerning the thermal performance specification of the envelope of the "Energy Saving Design Standards for Public Buildings" [24].

3.3. Multi-Objective Coupled Simulation and Optimization Experiment

A parametric model is established according to the functional partition, and the basic parameter information is determined concerning the domestic library building design specifications (Table 2). This model simulates the light and heat environment and energy consumption (Figure 4). The model was developed using the grasshopper platform and the Python language, allowing the model to invoke the Energyplus and Radiance simulation engines running in the background and to implement optimized design of experiments by integrating the SPEA-2 optimization algorithm.

Table 2. List of architectural model parameters of the library atrium.

Parameter Type	Parameter Name	Parameter Value
Geographical Location and Climate Conditions	Thermal Zone	Severe Cold Region
	Meteorological Data	Shenyang CSWD Meteorological Data
	Building Orientation	South-North Orientation
Atrium Space Interface	Atrium Location	Core Type (Four-Sided) Atrium
	Number of Floors	3
	Floor Height	4.5 m
	Plan Shape	Rectangular
	Plan Shape	10 m × 12 m
	Plan Dimensions	Rectangular
	Daylighting Type	Top Lighting
	Skylight Spacing	2 m
	Skylight Area Ratio	0.2
Functional Space of Surrounding Buildings	Plan Dimensions	40 m × 40 m

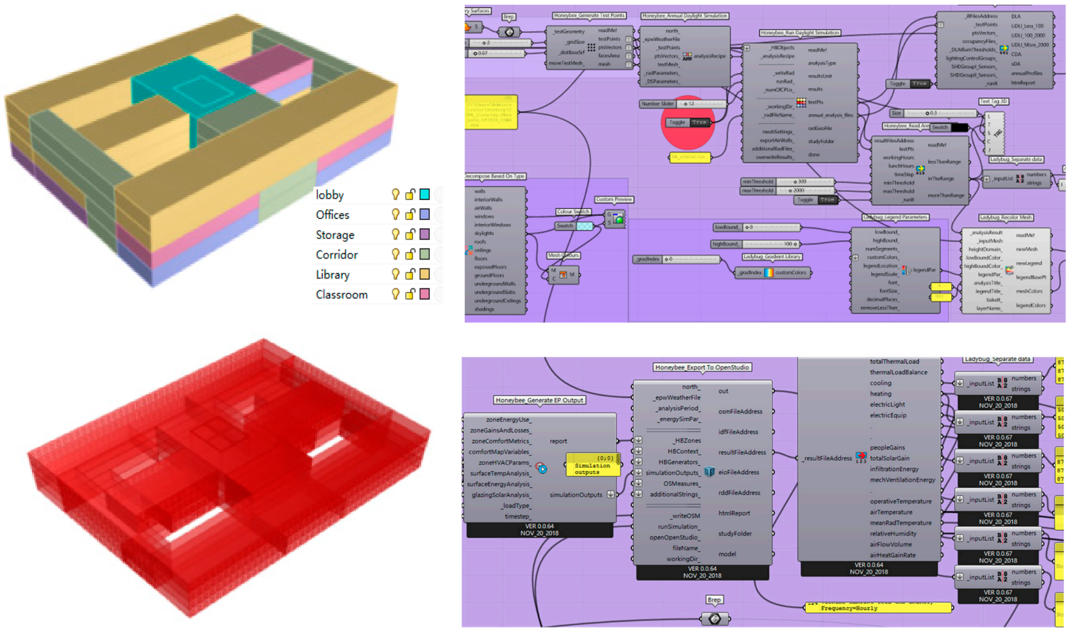


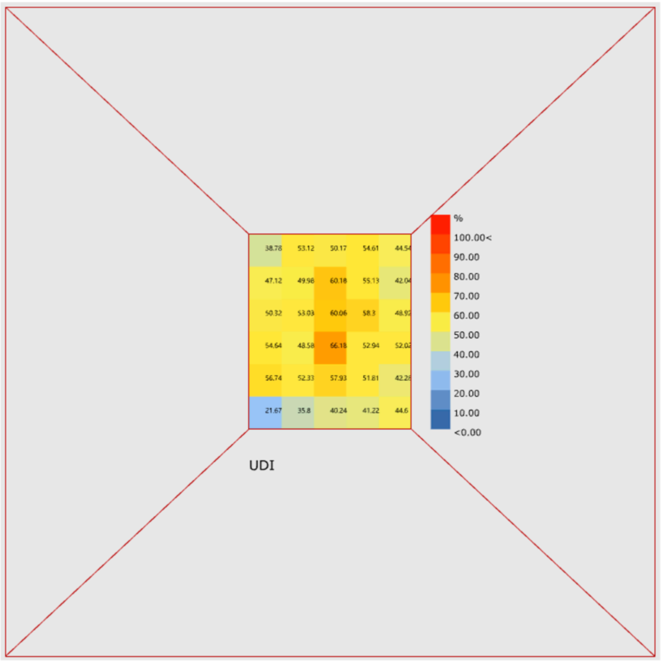
Figure 4. Atrium baseline model diagram and flowchart of photothermal environment and energy consumption simulation.

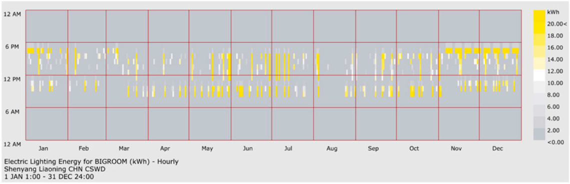
3.3.1. Light and Heat Environment, Energy Consumption Simulation

Comprehensive simulation results of the library atrium, as shown in Table 3, the status quo unit area cooling, heating, and lighting energy consumption of 54.6, 110.5, and 4.9 kwh/m^2. In order to facilitate the analysis of experimental data, there will be a year of experimental data by hour visualization (Figure 5); after the analysis of the data, we learned that only 45.2% of the time a year, the UDI value of the standard, more than half the time of the light conditions do not meet the standards. Lighting conditions do not meet the standard; a comprehensive analysis of the previously measured research data shows that the light and heat environment must be optimized further.

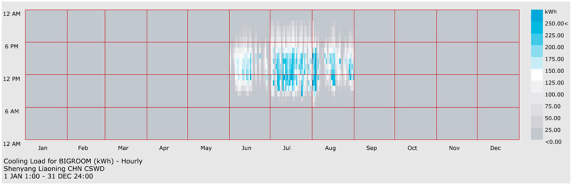
Table 3. Experimental data of library atrium simulation.

Name	Effective Natural Illuminance UDI (%)	Energy Use Intensity EUI (kWh/m^2)	Cooling Energy Use per Unit Area (kWh/m^2)	Heating Energy Use per Unit Area (kWh/m^2)	Lighting Energy Use per Unit Area (kWh/m^2)	Equipment Energy Use per Unit Area (kWh/m^2)	Total Energy Use (kWh)
Data	45.2	226.2	55.1	120.0	4.3	46.7	361,856

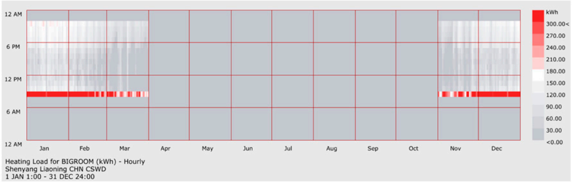




(**a**) Experimental data on lighting energy consumption



(**b**) Experimental data on refrigeration energy consumption



(**c**) Experimental data on heating energy consumption

Figure 5. Visualization of experimental data on energy consumption for lighting, refrigeration and heating.

3.3.2. Multi-Objective Optimization Principle and the Setting of Variables and Objectives

Comprehensive library data analysis of the current situation of its light and heat environment are optimization space, energy consumption, and the two building performance constraints between the relationship exists in order to seek to meet the high efficiency of the natural lighting, high satisfaction of the thermal environment but also to achieve the requirements of the low energy consumption program, the need to seek trade-offs between multiple objectives, and previous single-objective optimization can not be satisfied, so the multi-objective optimization of the coupled optimization technology routes and program module seeks to analyze the Adaptation function when dealing with more than one there is a mutual influence relationship and optimization at the same time, the careful consideration of multiple optimization objectives under the premise of finding the optimal Pareto optimal solution set or called the non-dominated solution set. In the parameter optimization experiments on the building, we would like to optimize the design of the skylight and building structure dimensions in the atrium area of the building. By changing the occupancy and size of the skylights, the building envelope dimensions are changed, along with the parameter feedback of the building structure. The parameters used reflect the modification of the skylight design, as well as the modification of its surrounding structure.

(1) Setting the range of values of optimization variables

The ratio of light transmission and opacity of the roof of the public building shall not be greater than 2:8. Therefore, the area ratio of the skylight is selected as 0–0.2 (changing in steps of 0.01), the height of the atrium is selected as 3–5 m (changing in steps of 0.1 m). The size of the plane of the atrium's through-height portion is selected as 10 m~30 m (changing in steps of 1 m). Keeping the peripheral size of the atrium of the university library building 40 × 40 m, the window spacing 5 m, and the height 12 m unchanged, the spatial interface (skylight area ratio) and spatial scale (atrium area ratio) are analyzed, respectively:

A. Spatial interface–skylight area ratio

Setting the atrium (square) of the through-height part of the plane with a length and width of 30 m. The skylight lighting area ratio is 0.01 as the growth gradient, so the skylight area ratio n takes the values of {n=0.01, 0.02, 0.03, 0.04, 0.05, 0.06, 0.07, 0.08, 0.09, 0.10, 0.11, 0.12, 0.13, 0.14 0.15, 0.16, 0.17, 0.18, 0.19, 0.2}

B. Spatial Scale–Atrium Area Ratio

The skylight lighting area ratio is set to 0.2. The length and width dimensions of the atrium (square) of the through-height part are increased by a gradient of 1 m. Therefore, the atrium area ratio n values are {n = 6.25, 7.56, 9.00, 10.56, 12.25, 14.06, 16.00, 18.06, 20.25, 22.56, 25.00, 27.56, 30.25. 33.06, 36.00, 39.06, 42.25, 45.56, 49.00, 52.56}.

(2) Setting the optimization objective

The Octopus operator seeks the minimum objective parameter, which needs to be multiplied by -1 to convert to a negative form when the optimization objective is the maximum value. In this paper, the optimization objective energy consumption per unit area (EUI) needs the objective to be minimized without processing. In contrast, the effective natural light intensity (UDI) needs the objective to be maximized, which will be multiplied by -1 to deal with.

(3) Setting optimization parameters

The variable parameters (atrium length and width, story height, window spacing of skylight, skylight area ratio) and the target parameters (UDI, EUI) are connected to the G-end and O-end of Octopus for optimization experiments, respectively, and the other relevant setting parameters are shown in Table 4. After the parameters are set, the optimization experiment is initiated, and the optimization goal of reaching the equilibrium point is sought and recorded through the arrangement operation between the domains of each parameter value.

Table 4. Related parameter settings.

Elitism	Mutation Probability	Mutation Rate	Crossover Rate	Population Size
0.5	0.2	0.9	0.8	70

4. Experimental Results, Analysis, and Discussion

4.1. Analysis and Verification of Optimization Results

(1) Spatial interface–skylight area ratio

Using SPSS to correlate and fit the analysis between the skylight area ratio and the dependent variables (Table 5), the skylight area ratio correlation with the dependent variables is significant, followed by a regression analysis of the experimental data and its R-square showing that the fit is good, which further confirms that the changes in the skylight area ratio can cause changes in lighting, temperature, and energy consumption, which the analysis of the results of the experiments of the multi-objective optimization can follow up.

With the increase in skylight area ratio, the lighting energy consumption decreases from 27.8 kwh/m^2 to 1.1 kwh/m^2, while the cooling energy consumption increases from 44 kwh/m^2 to 53.4 kwh/m^2, and the heating energy consumption increases from 88.9 kwh/m^2 to 104.1 kwh/m^2. It is confirmed that the increase in lighting area and the reduction in lighting energy consumption while bringing heat exchange will increase air-conditioning energy consumption. The skylight area ratio increases in the range of 0–0.11, and its UDI value increases from 0.8% to 74.7% in the range of 0.11–0.2 and its UDI value decreases from 74.7% to 55%, and the skylight area ratio increases in the range of 0–0.04, and its EUI value decreases from 207.4 kwh/m^2 to 191.2 kwh/m^2, and in the range of 0.04–0.2 increase, its EUI value increases from 191.2 kwh/m^2 to 205.3 kwh/m^2. These data conclude that the effect of the skylight area ratio on lighting satisfaction and comprehensive energy consumption is segmented. The decrease in lighting energy consumption leads to the increase in UDI and the decrease in EUI when the skylight area ratio is increased in a small range, while the UDI shows a decreasing trend when it is increased in a more extensive range and at the same time, the EUI shows a growing trend due to the increase in the air conditioning energy consumption (Figure 6). In summary, the experiment confirms that the increase in skylight area can bring better lighting conditions to the room, reducing the lighting energy consumption to compensate for the lighting shortage showing a trend of reduced comprehensive energy consumption. However, the glare caused by the oversized skylight area leads to a decrease in lighting satisfaction, and the increase in air conditioning energy consumption has a more significant impact than the decrease in lighting energy consumption, which leads to an increase in comprehensive energy consumption; therefore, it is necessary to further discuss the skylight area ratio and which value range to achieve the photothermal equilibrium.

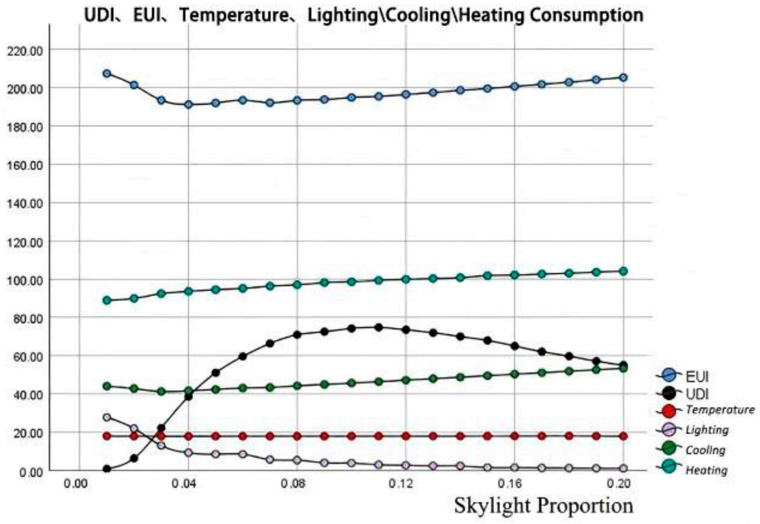


Figure 6. Trend graph of simulated experimental data of skylight area ratio.

Table 5. Correlation and fit of skylight area ratio to design target.

	Effective Natural Illumination (UDI)	Temperature (T)	Energy Consumption per Unit Area (EUI)	Cooling Energy Consumption	Heating Energy Consumption	Lighting Energy Consumption
correlation coefficient	0.607	0.658	0.465	0.962	0.980	−0.817
Sig	0.005	0.002	0.039	0.000	0.000	0.000
R-square	0.988	0.910	0.888	0.988	0.993	0.897

(2) Spatial scale–atrium area ratio

Using SPSS to analyze the correlation and goodness of fit between the atrium area ratio and the dependent variables (Table 6), the correlation between the atrium area ratio and the dependent variables is significant, followed by regression analysis of the experimental data and its R-square show that the goodness of fit, which further confirms that the changes in the atrium area ratio can cause changes in lighting, temperature, and energy consumption, which can be followed up with the analysis of the results of the multi-objective optimization experiments.

The experimental data of atrium area ratio show three trends (Figure 7), in the range of a 6–14%, increase in UDI value from 35% to 78%, heating energy consumption from 96.9 kwh/m^2 to 100.1 kwh/m^2, cooling energy consumption from 45.94 kwh/m^2 to 45.56 kwh/m^2, lighting energy consumption from 7 kwh/m^2 to 1.2 kwh/m^2, EUI value from 196.6 kwh/m^2 to 193.6 kwh/m^2; in the range of 14–46%, increase in UDI value from 78% to 56%, heating energy consumption from 100.1 kwh/m^2 to 95.4 kwh/m^2, refrigeration energy consumption from 45.56 kwh/m^2 growth to 47.46 kwh/m^2, lighting energy consumption from 1.2 kwh/m^2 growth to 12.3 kwh/m^2, EUI value from 193.6 kwh/m^2 to 201.93 kwh/m^2; in the range of 46–56%, increase in UDI value from 56% to 74%, heating energy consumption from 95.4 kwh/m^2 to 98.6 kwh/m^2, cooling energy consumption from 47.46 kwh/m^2 to 45.65 kwh/m^2, lighting energy consumption from 12.3 kwh/m^2 to 3.9 kwh/m^2, and EUI value from 201.93 kwh/m^2 to 194.83 kwh/m^2. In summary, it is confirmed that, when the atrium area ratio increases, the UDI value shows a trend of increasing and decreasing, and the trend of comprehensive energy consumption is the same as that of lighting and refrigeration energy consumption and opposite to that of UDI and heating energy consumption. Therefore, it is necessary to discuss further in what value range the atrium area ratio can reach the light–heat balance.

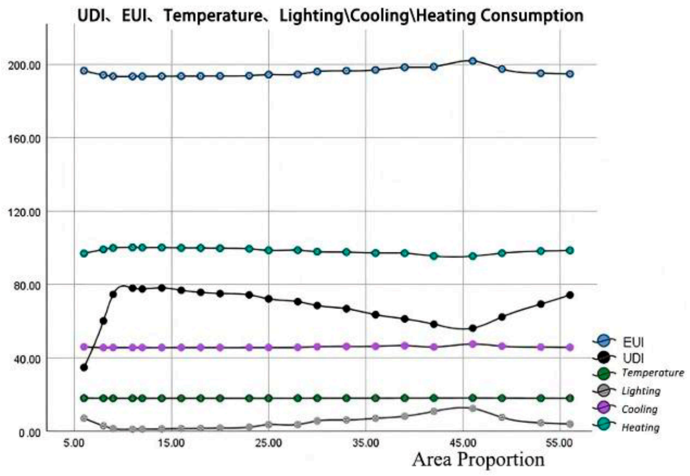


Figure 7. Atrium area ratio simulation experimental data trend graph.

Table 6. Atrium area ratio and design target correlation and fit.

	Effective Natural Illumination (UDI)	Temperature (T)	Energy Consumption per Unit Area (EUI)	Cooling Energy Consumption	Heating Energy Consumption	Lighting Energy Consumption
correlation coefficient	−0.381	0.615	0.604	0.520	0.621	0.623
Sig	0.016	0.003	0.004	0.016	0.003	0.003
R-square	0.675	0.862	0.834	0.617	0.870	0.874

4.2. Analysis of Multi-Objective Coupled Optimization Experiment Results

In order to further explore the value range of the skylight area ratio and atrium area ratio, continue to carry out iterative computing experiments; after a total of 42 generations of 125 h of computation, the results in the panel tend to stabilize, the parameter distance map and the target convergence diagram show that the results are sufficiently convergent. At this time, the final results can be used to derive the distribution of 40 generations of the solution, which will be the 5th/10th/15th/20th/25th/30th/35th/40th generation of records. As shown in the figure, it can be seen that, from the 15th to 30th generation, the solution panel can be stabilized, and after that, the changes are few (Figure 8).

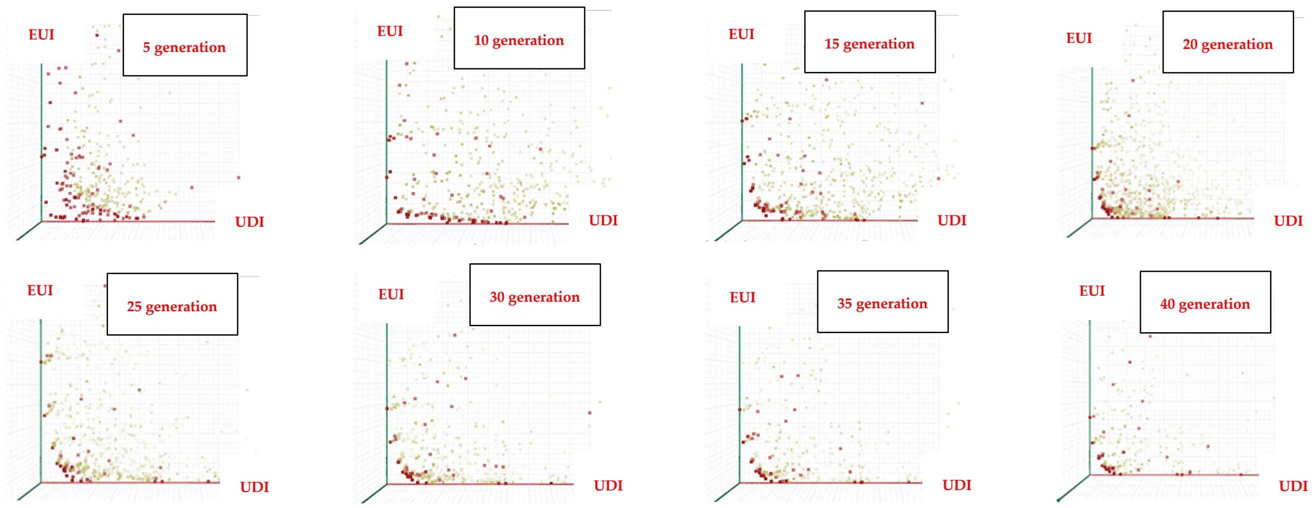


Figure 8. Optimized Pareto solution distribution diagram.

At this point, the solution panel of the 40th generation is extracted, and the 13 non-dominated solution sets (optimal solutions of the Pareto front) are recorded, while the corresponding variation coefficients, as well as the objective values of their optimization, are listed separately, as shown in Table 7.

Table 7. Optimal solution set experimental data.

Name	**Unit**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Length	m	26	26	26	26	30	26	27	30	30	30	19	19	22
Width		25	25	26	26	30	26	26	30	30	30	27	26	27
Floor Height		3	3	3	3	3	3	3	3	3	3	3.2	3.2	4.3
Area Proportion	%	41	41	42	42	56	42	44	56	56	56	32	31	37
Skylight Proportion		4	5	6	7	7	8	8	8	9	10	17	18	14
Window Spacing	m	6	6	6	6	5	6	6	5	5	5	6	6	6
UDI	%	50.26	60.28	66.34	69.27	69.74	70.63	70.72	71.57	72.38	72.56	72.62	72.77	72.84
EUI	Kwh/m^2	119.37	119.54	120.24	120.73	121.14	121.45	121.71	121.87	122.43	123.50	131.67	132.39	141.36
Cooling Energy Consumption	Kwh	15.95	16.25	16.56	16.89	16.96	17.16	17.24	17.23	17.59	17.92	19.81	20.13	20.38
Heating Energy Consumption		47.26	48.31	49.07	49.63	49.75	50.65	50.35	50.49	50.93	51.64	56.95	57.4	65.90
Lighting Energy Consumption		4.62	3.33	2.86	2.39	2.59	1.70	2.20	2.21	1.89	1.82	1.67	1.53	1.83
Equipment Energy Consumption		51.53	51.65	51.75	51.82	51.85	51.95	51.92	51.94	52.02	52.12	52.92	52.99	53.82
Total Energy Consumption		190,987	191,258	192,385	193,171	193,832	194,326	194,733	194,994	195,882	197,601	210,665	211,818	226,174

Observing the experimental data of the 13 groups of optimal solutions, it can be seen that, with the increase in the proportion of skylight area, the heat exchange brought about by the increase in cooling energy consumption and heating energy consumption far exceeds the reduction in lighting energy consumption, so that the final total energy consumption per unit area (EUI) still increases. Therefore, in order to explore the dynamic relationship between the atrium light, heat environment, and energy consumption values under the influence of multiple parameters and to show the simulated optimized experimental scheme more clearly and intuitively, the three sets of experimental data with the lowest UDI and the lowest EUI (Plan 1), the highest UDI and the highest EUI (Plan 13), and the optimal UDI and the optimal EUI (Plan 8), respectively, were selected for model construction (Figure 9). Comprehensive analysis of the optimization scheme shows that the extreme optimization scheme can ensure that the integrated energy consumption is reduced to a minimum under the conditions of the lighting. Under a substantial increase in the reduction of its integrated energy, consumption is not very significant, so the extremely preferred option is discarded. Comparing the simulation data in the previous section, we know that the atrium area ratio is optimized from 8% to the value range of 31–56%, the atrium skylight area ratio is optimized from 20% to the value range of 4–18%, the atrium skylight window spacing is optimized from 2 m to the value range of 5 m–6 m, and the atrium floor height is optimized from 3.5 m to the value range of 3 m–4.3 m. The optimized effective natural light intensity (UDI) increases by 5.2% from 45.2% to 4.3 m, and the optimized UDI increases by 5.2% from 5.2% to 5.3 m. 45.2% increased by 5.06–27.64%, energy consumption per unit area (EUI) from 226.20 kwh/m^2 reduced by 84.84 kwh/m^2–106.83 kwh/m^2. Therefore, the optimization scheme within the above value range can meet the optimized atrium light environment quality, and energy efficiency is effectively improved, which confirms the feasibility of the research and development of the building light–heat coupling optimization technology route and program module.

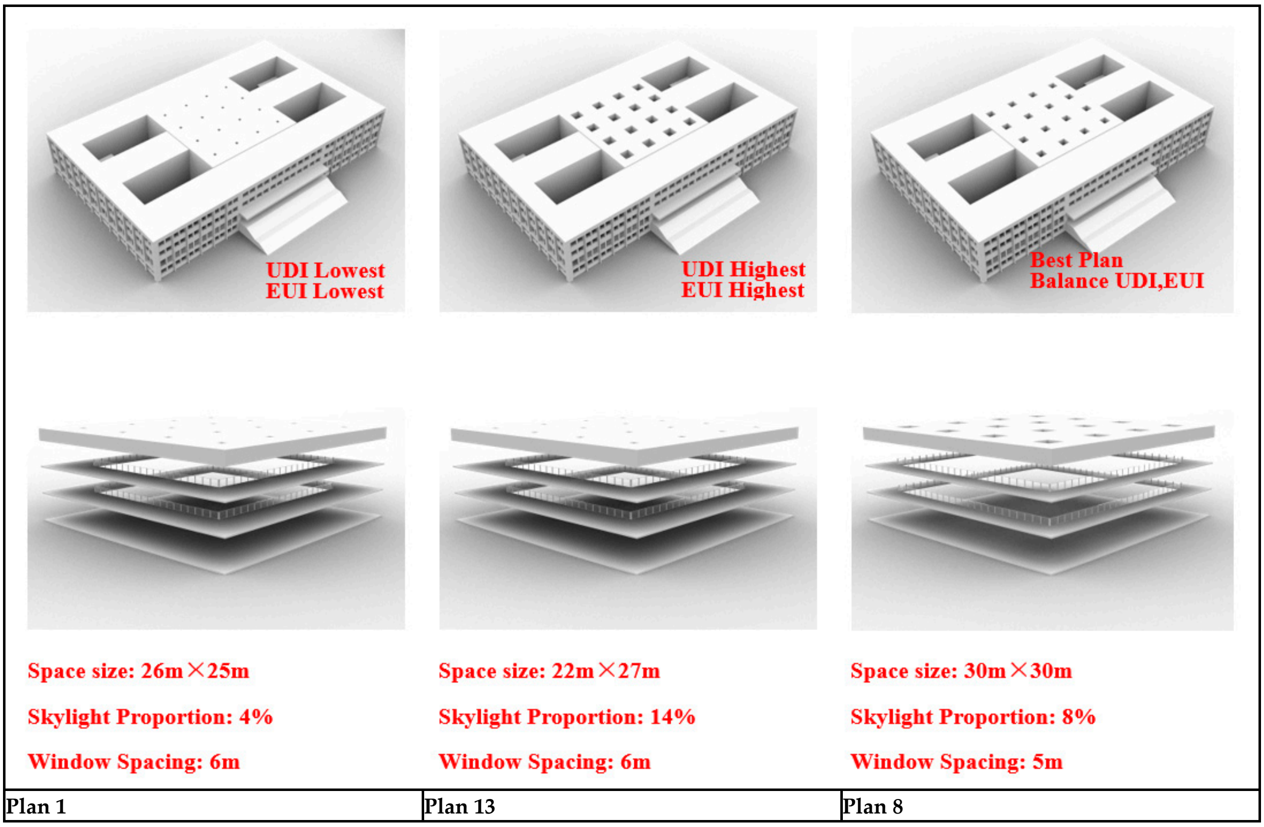


Figure 9. Atrium experimental data model diagram.

5. Conclusions and Prospect

This study presents a multi-objective optimization approach for balancing daylighting and thermal performance in university library atriums located in cold regions. Through a parametric simulation framework incorporating EnergyPlus, Radiance, Daysim, and OpenStudio, we explored the complex interactions between daylight availability, thermal comfort, and energy consumption. By employing the Octopus optimization module and Pareto optimization principles, we systematically identified optimal design parameters that enhance natural illumination while reducing heating, cooling, and lighting energy demand.

The results demonstrate that optimized atrium configurations can significantly improve energy efficiency while maintaining adequate daylight levels. Specifically, after parameter optimization, the effective useful daylight illuminance (UDI) increased by 5.06–27.64%, while the annual energy use intensity (EUI) was reduced by 84.84–106.83 kWh/m^2. These findings confirm the feasibility of an integrated light–heat coupling optimization strategy for sustainable building design.

This research provides valuable insights for architects and designers aiming to improve the energy efficiency of atrium spaces in cold climates. The proposed parametric methodology offers a quantitative framework for early-stage decision-making, allowing for the systematic exploration of geometric and spatial configurations to achieve an optimal light–heat balance. Future work could extend this approach by incorporating advanced machine learning techniques for real-time adaptive optimization and investigating the applicability of the method in different climatic contexts.

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