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A Study on Parametric Design Method for Optimization of Daylight in Commercial Building's Atrium in Cold Regions

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Abstract: With the development of urbanization, more and more commercial buildings are built in cities, which is resulting in a large amount of building energy consumption that threatens the ecological environment of the earth. Lighting energy in commercial buildings occupies a large proportion of consumption, and improving the quality of natural daylight in commercial atriums is of great significance for building energy efficiency as well as improving indoor comfort. This paper proposes a method for optimizing the daylight quality of commercial atriums. Starting from the perspective of parametric design, this paper investigates the current status and theoretical research on the natural daylight of commercial atriums in cold regions, taking Jinan, China, as an example. Dynamic daylight and glare simulations were performed using Rhino + Grasshopper and Ladybug + Honeybee for every design parameter in the system, followed by correlation analysis and multiple linear regression analysis using SPSS to determine the degree of influence of each design parameter on the daylight quality of the atrium. Based on the results of the above analysis, the multi-objective optimization plug-in Octopus is used to find the combination of design parameters that can achieve the best indoor daylight. The results show that among a total of fourteen atrium design parameters, seven of them are significantly correlated with atrium daylight, and after regression analysis, it is found that the atrium design parameters affect the atrium daylight and glare in the following order: Skylight VT, Skylight ratio, Atrium inclination, Fabric coverage, Fabric VT, Wall reflectivity, Roof reflectivity. The optimal design parameters for commercial atrium daylight quality are obtained according to the Pareto front solution set, which provides some reference and ideas for improving the optimization of commercial atrium daylight in cold regions of China.

Keywords: daylight; atrium; parametric design; multi-objective optimization; sensitivity analysis

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1. Introduction

At present, the world is facing a variety of problems such as an energy crisis, ecological damage, and climate warming, while the construction sector occupies a large proportion of energy consumption, accounting for about one-third of the total social energy consumption [1]. Most city dwellers spent nearly 90% of their time indoors. In 2008, only half of the world's population lived in urbanized areas; however, they consumed nearly 67% of the world's energy. By 2030, the proportion is expected to increase to 73% [2,3]. Therefore, the study of indoor comfort and energy saving will have a positive impact on the ecological environment and human health [4]. In the light of the rapid development of China's urbanization and people's high pursuit of material and spiritual life, cities in China have achieved the transformation from "production-oriented cities" to "life-oriented cities", and urban commerce also proceeds on the path of rapid growth. Nowadays, retail-centered business has grown into an indispensable part of the process of expanding domestic demand and optimizing the economic structure. More and more high-tech, luxurious and fashionable shopping malls are being built in cities, whose current application of colorful lights accounts for a lot of daylight energy consumption. Hence, it is important to improve the quality of natural daylight in commercial buildings.

Commercial buildings consume large amounts of energy, and this kind of consumption is expected to increase in the future because artificial lighting is a key factor in high-level energy consumption. The fact is that the application of artificial lighting generates heat and causes cold, which increases cooling loads, which account for about 3–5% of the total energy consumption. Decreasing the use of artificial lighting is of great significance for lowering the total energy consumption in commercial buildings. A commercial building's atrium not only connects interior spaces but also is a place for social activities, thus bearing aesthetic and iconic features as well as providing light to the core of the building [5]. Atriums are widely used by designers in commercial building design because they usually have a daylight roof, which is one of the most commonly used elements in the design of indoor shopping malls. Its main purpose is to provide natural daylight for the atrium space and the enclosed space of the corridors [6–8]. From the perspective of architectural design, since an atrium is the core design point of commercial buildings, architects usually take advantage of natural daylight, which not only can reduce daylight energy consumption and heat dissipation but also creates a vibrant business atmosphere [9]. At present, atriums have become a trend in modern commercial design because they absorb natural light and connect adjacent spaces with the outside world [10]. Numerous studies have demonstrated the use of natural daylight in commercial spaces to increase sales performance and office rental value, improve building users' health, and enhance customer satisfaction [11–13].

Natural daylight is both an essential part of green buildings and an important part of passive design [14]. The use of natural daylight not only helps reduce the energy consumption of lamps but also increases visual comfort, which is key to the improvement of indoor environments. Achieving proper daylight can improve work performance, provide a better environment for building users, and have a positive psychological impact on building users [15–18]. At present, people increasingly prefer natural daylight to artificial lighting in the built environment; sunlight has a positive impact on the physical and psychological well-being of building users [19,20]. The color rendering index of natural light is the best among all light sources, with daylight quality and energy-saving effect that are superior to those of artificial lighting [21,22]. It has been confirmed that natural daylight improves students' learning and social skills in schools [23] and also contributes to the rehabilitation of the elderly and other hospital patients [24,25]. Beneficial to physical health, appropriate ultraviolet rays have the function of sterilization and disinfection [22]. However, excessive sunlight exposure can also cause adverse effects, such as optic glare and overheating in buildings, especially the adverse reactions in the human body stimulated by exposure to sunlight. The discomfort caused by visual effects such as glare are more common than by heating effect [26–29].

Since the atrium is the main area of natural daylight in shopping malls, the exploration of changes in its design parameters plays a crucial role in optimizing the indoor daylight performance of buildings [30]. Therefore, by selecting and extracting a large number of atrium design parameters (e.g., atrium size, atrium inclination, atrium material, skylight design, shading parameters) from a large number of studies related to atrium design parameter variables. This paper uses the parametric software Rhino + Grasshopper to build a parametric model of typical atrium daylight in cold regions of China. Specifically, the paper:

(1) Adopts the Ladybug + Honeybee daylight simulation plug-in to perform dynamic daylight and glare simulation.
(2) Conducts correlation analysis and multiple linear regression analysis for each design parameter based on the simulation results to determine the impacts of different parameters on atrium daylight.
(3) Uses the multi-objective optimization tool Octopus to calculate the optimal parameter combination for optimizing atrium daylight.

The optimal combination of parameters can achieve the best annual daylight and anti-glare effects, thereby improving the daylight performance of commercial buildings' atriums in cold regions of China.

2. Research Methodology and Model Building

2.1. Field Research on the Daylight of Commercial Building's Atrium

2.1.1. Cold Regions of China

Most of the cold regions in China are located in the north. The typical climate is cold winter and hot summer, which requires heat preservation in winter and heat insulation in summer; at the same time, it is necessary to enhance solar radiation in winter and sun shading and heat insulation in summer. Taking Jinan, China, as the research site and the atrium of a commercial shopping center in Jinan as the research object, this paper aims to investigate the optimization of daylight of a commercial building's atrium in a cold region of China.

The latest method for evaluating daylight performance is climate-based daylight modeling (CBDM), which is a dynamic method based on real daylight climate data hour by hour throughout the year, making daylight simulation more accurate and reliable. CBDM provides various metrics for evaluating daylight performance, such as spatial daylight autonomy (sDA), annual sunlight exposure (ASE), and useful daylight illuminance (UDI) [5–7,12,13,30,31]. Therefore, the Shandong Jinan (CSWD) file downloaded from https://energyplus.net/weather (accessed on 23 November 2021) serves as the weather file for the later daylight simulation study.

2.1.2. Test Objects and Settings

According to different locations, atriums generally can be classified into four types: enclosed atriums, semi-enclosed atriums, linear atriums, and attached atriums (Figure 1). The closed atrium is the classic or standard type, and the most common one. It can be any shape on the plane, such as a square, rectangle, circle, or triangle. The daylight roof or skylight is the only source of daylight and view [32].

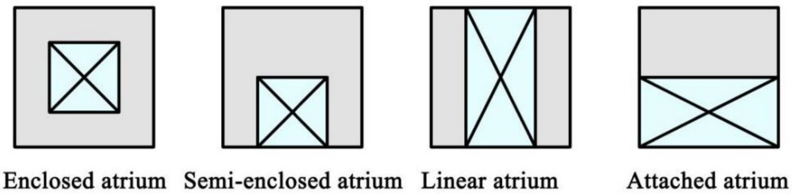

Figure 1. Different types of atriums.

The enclosed four-way atrium is chosen for the object of study. Compared with the other forms of atrium spaces, this kind of atrium is connected to the interior in all four directions. Light can only enter through skylights, without the side windows to assist in daylight, which is the most unfavorable situation for an indoor daylight environment. At the same time, this form excludes the daylight influence of side windows and allows for a more systematic and in-depth study of the degree of the impact of daylight roof design on atrium daylight [33].

The atrium of a shopping mall in Jinan, China (Figure 2), is selected as the test object. The plane shape of the atrium is rectangular, with a length of 30 m, a width of 24 m, and a height of about 20 m for 5 floors. The field test of illuminance is conducted according to the Chinese daylight measurement specification "daylight Measurement Method GB/T5699-2017": The test time lasted from 10:00 a.m. to 16:00 p.m. on 22 December 2021, the winter solstice day. The weather was full overcast. The test instrument was a FLUKE-941 illuminance meter, which is small, portable, and convenient for handheld measurement and real-time recording of the illuminance value of the measurement point. For the test, the measurement points were arranged in uniform layout along the length and width of the atrium, the space between which was about 3 m. There were five measurement points, whose distance from the indoor edge of the shopping mall was about 5 m. Along the atrium axis were generated five horizontal and five vertical test sections. The measurement took a horizontal plane 0.75 m above the ground as the reference plane (Figure 3).

Figure 2. Shopping mall atrium photos.

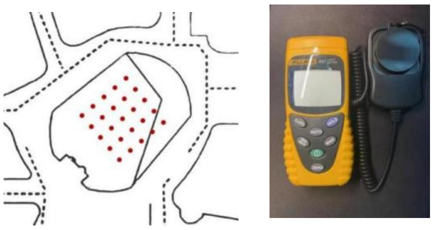

Figure 3. The test equipment and measuring point layout.

When measuring, hold the instrument to read the illuminance value and record at the same time. After each measuring point stabilizes the instrument, read the data, and then quickly go to the next measuring point to measure. This process is repeated twice, while attempting to make the measurement process as fast and accurate as possible. The illuminance values of all measuring points are averaged to obtain the average illuminance of the commercial building's atrium.

2.1.3. Testing Results

The test results are shown in Table 1.

Table 1. Atrium illumination measurement results.

Time	Average Illumination (lx)	Daylight Factor (DF)	Outdoor Illumination (lx)
10:00	968	11.64%	8313
11:00	876.32	11.90%	7362
12:00	686.64	9.05%	7588
13:00	592.4	11.72%	5054
14:00	544.56	10.63%	5125
15:00	397.6	11.46%	3469
16:00	299.44	11.14%	2688

2.2. Typical Model Building

2.2.1. Software Selection

At present, there is a variety of software with different functions for simulating indoor daylight in buildings. Common daylight analysis software includes Lightscape, Desktop Radiance, Daysim, DIVA, Lumen Micro, Ecotect, and Dialux [34]. Since this research is based on the perspective of parametric design, Rhino + Grasshopper is selected as the modeling software, assisted by Ladybug + Honeybee, the built-in building physical environment simulation software in Grasshopper, as the tool for daylight performance simulation. Its advantages include not only the Radiance + Dayism calculation engine to ensure the accuracy of the annual daylight and glare simulation but also the convenience of the parametric modeling function of Grasshopper to adjust the design parameters of commercial buildings' atriums, so as to explore their effect on indoor daylight. Finally, the multi-objective optimization software Octopus built into Grasshopper can also be used to calculate the trade-off between annual daylight and glare simulation to achieve the best results for the indoor daylight of a commercial building's atrium.

2.2.2. Typical Model Parameter Settings

According to the literature research and the field research of commercial buildings' atriums in Jinan, a model of a typical commercial building's atrium in a cold region is established in Grasshopper (Figure 4). The specific design parameters are shown in Table 2.

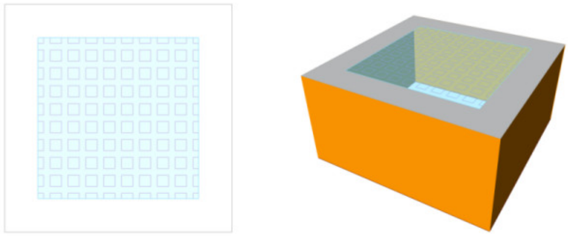

Figure 4. Grasshopper model build image.

Table 2. Typical model parameters (WI = Well Index; VT = Visible light transmittance).

Atrium Parameters	Value
Length	30 m
Width	30 m
Height	15 m (4 floors)
WI	1
Area	900 m^2
Indoor reflectivity	0.8/0.5/0.2
Atrium shape	Rectangle
Skylight ratio	0.5
Skylight VT	0.6
Skylight Form	Flat skylight
Shading system	50% coverage fabric shade

2.3. *Verification of Daylight Model*

The measured illuminance data will be used for verifying the illuminance simulation results of the typical model [35], so as to determine the reliability of the typical model established. Under the same outdoor illuminance conditions, the illuminance of the typical model is simulated on an hourly basis using L + H (Ladybug + Honeybee), and then a correlation analysis between the illuminance value is obtained from the simulation, and the measured data are conducted to verify whether the two are significantly related and whether the establishment of the typical model is reliable. The specific analysis is shown in Figure 5).

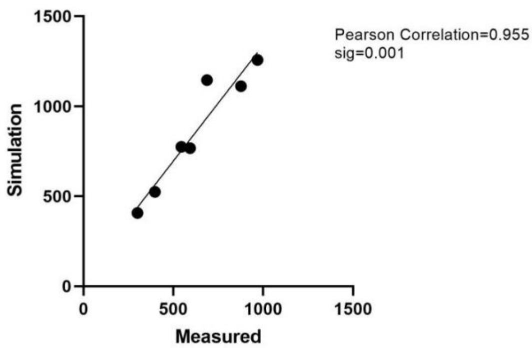

Figure 5. Typical model reliability analysis.

Due to the influence of skylight stains and window frames, and the presence of long hours of artificial lighting and partial shading from other buildings at the atrium site, there is a certain error between the measured illuminance and the software simulation value; the Pearson correlation calculated by correlation analysis is 0.955, with sig = 0.01 less than 0.05. The results indicate that there is a significant correlation between the established typical model daylight and real building daylight in cold regions of China, and subsequent daylight simulations can be performed.

3. Dynamic Daylight and Glare Simulation

3.1. Investigation on Design Parameters of Atrium Daylight and Light-Environment Evaluation Index

After the typical model is established, it is necessary to determine the design parameters affecting the quality of light for the study. Common design parameter variables usually include orientation, window-to-wall ratio, window material, and shading length [36]. Through the analysis of relevant literature research, the design parameters that affect atrium daylight are analyzed and screened with the specific results shown in Table 3.

Table 3. Research on atrium daylight literature. (Definition of Abbreviations: WI = Well index; VT = Visible light transmittance; PAR = Plane aspect ratio; SAR = Space aspect ratio; WWR = Window to wall ratio; DF = Daylight factor; ADF = Average daylight factor; UDI = Useful Daylight Illuminance; DA = Daylight Autonomy; CDA = Continuous Daylight Autonomy; sDA = Spatial Daylight Autonomy; ASE = Annual Sunlight Exposure; DGP = Daylight glare probability).

Author	Year	Independent Variable	Dependent Variable
B.Calcagni [10]	2004	WI; Skylight VT; Skylight Form	DF
Ran Yi [32]	2009	PAR; SAR; WI	DF
Jiangtao Du [35]	2011	Atrium Reflectance; PAR	ADF
Stanley K.H. Chow [18]	2013	Atrium Size; daylight Control	Illumination; DF; Energy Consumption
Abdelsalam Aldawoud [37]	2013	Atrium Size; Skylight VT; Skylight Ratio; Climate	Energy Consumption
Umberto Berardi [7]	2014	Skylight VT; Shading System	DF; UDI; DGP
Mahsan Mohsenin [12]	2015	WI; Skylight Form; Atrium Reflectivity; Skylight VT	sDA; ASE
Mohsen Ghasemi [8]	2015	Atrium Shape; Atrium Size	ADF
Milica Vujošević [38]	2017	Atrium Shape; Shading System	Energy Consumption
Wessam El-Abd [6]	2018	Skylight Ratio; Skylight VT	DA; Glare Index; Energy Consumption
Ignacio Acosta [39]	2018	Atrium Height; Skylight VT	DF
Francesco De Luca [40]	2018	Skylight Orientation; Skylight VT	CDA; UDI
Jie Li [13]	2019	Atrium Shape; Atrium Size; Skylight Ratio	sDA; DA
Kareem S.Galal [41]	2019	Skylight VT	sDA; ASE; UDI
Omar S.Asfour [31]	2020	WWR; Shading System; Skylight	Energy Consumption; DF; sDA; ASE
Mohamed Marzouk [42]	2020	Skylight Form; Skylight Ratio; Skylight Orientation	sDA; ASE; UDI
Mahsa Rastegari [30]	2021	WI; Atrium Size	DA; UDI
Zhengyu Fan [33]	2021	Skylight Material; Skylight Ratio	DA; UDI
Om Prakash [43]	2021	Atrium Shape; Skylight Orientation	DF; Energy Consumption
Lili Dong [44]	2022	Atrium Shape; Atrium Inclination; Skylight Size	DF; Illumination Uniformity
Mohamed Marzouk [45]	2022	Skylight VT; Skylight Size	sDA; ASE

It can be seen from the table that the design parameters that affect atrium daylight as independent variables are mostly atrium size, skylight ratio, skylight VT, and shading system, while the daylight indicators in the dependent variables were mostly DF and illuminance uniformity in earlier years. In recent years, dynamic daylight evaluation indexes such as sDA, ASE, and UDI are frequently used, while glare evaluation often takes DGP as the evaluation index.

Therefore, the variable setting of this study has taken the independent variables and dependent variables selected in these studies into full consideration, so as to achieve a more precise and comprehensive research conclusion.

3.2. Determination of Design Parameters and Variables Affecting Atrium Daylight

3.2.1. Design Parameters of Atrium

Atrium design parameters are the main components of atrium space. In recent years, there have been increasing studies on the optimization of atrium geometry, but the daylight performance has not been fully studied, and such research on daylight performance usually focuses on fixed architectural geometry [36]. The correct use of building design parameters, as well as other elements such as shading, energy efficient glazing, room geometry, and building systems, will significantly reduce building energy consumption and improve building physical performance [46]. Common types of atrium geometries include circular, rectangular, and triangular, and different floor plans affect the amount of daylight entering the building. Additionally, the height of the atrium has an unavoidable effect on the incoming daylight, with WI or well index, which is related to the floor number, being regarded as an important variable [30].

First, the plane shape of the atrium is the design parameter that needs to be considered most in the early stage of the design. Once it is determined, it cannot be easily changed in the later stage. Now, its design is mostly based on the needs about shape and appearance, while it is rarely considered in combination with daylight performance. Second, the profile inclination of the atrium is also one of the factors affecting the daylight of the atrium. Daylight performance was measured in terms of atrium proportions as defined by the Well Index (WI) used to characterize atriums, a quantifier describing atrium proportions. The equation is $WI = H(W + L)/2\,WL$. According to this equation, the well index (WI) of a square atrium is measured by the length, width, and height of the atrium [12]. Based on the common commercial atrium design dimensions in China, a range of atrium dimensions is set, and the effects of different WI on atrium lighting under different dimensions are also studied. Third, the indoor reflectivity of the atrium is also one of the important factors affecting daylight. According to the requirements of Chinese regulations, ceilings, walls, and floors have different reflectance value ranges. Therefore, the atrium design parameters of size and reflectivity are set as the independent variables for the research (Table 4).

Table 4. Atrium design parameter values.

Atrium Design Parameter	Value	
Atrium size (AS)	Length	10–50 m
	Width	10–50 m
	Height	10–30 m
	WI	0.2–3.0
Atrium inclination (AI)	AI	60–120°
Indoor reflectivity (IR)	Roof	0.60–0.90
	Wall	0.30–0.80
	Floor	0.10–0.50

3.2.2. Design Parameters of Daylight Roof

The setting of external windows in a building plays a decisive role in daylight, and the daylight performance of a window system largely depends on factors such as window type and size, window orientation, and window opening ratio [47]. In atrium designs, window systems often come in the form of skylights. The skylight has a crucial impact on daylight, energy consumption, and the visual comfort of the atrium. The selection of its design parameters is part of the basic decision in the early design stage. Usually, parameters such as skylight form, orientation, and glass size in skylight design [27,48] are difficult to adjust later. Therefore, the design of daylight must be carefully studied and become part of the overall design process, with consideration of multiple aspects at the same time.

First, the roof form. Skylights usually adopt a flat-top roof, single-slope roof, double-slope roof, or four-slope roof, and changing the slope of the skylights will also affect the effect of indoor daylight. Second, the window opening ratio of the skylight, that is, the ratio of the skylight area to the area of the atrium roof, has a crucial impact on indoor daylight. The larger the window opening ratio, the better the indoor illumination but the more serious the glare, and vice versa. Third, another important design parameter is the transmittance of skylight glass, which directly affects the luminous flux of sunlight entering the room through the glass, and has a significant effect on indoor daylight. The specific range of daylight roof design parameters is shown in Table 5.

Table 5. Skylight design parameter values.

Skylight Design Parameter	Value
Skylight Ratio (SR)	0.10–0.90
Skylight VT (SV)	0.10–0.90

3.2.3. Design Parameters of the Shading System

While the atrium skylight brings natural daylight, it often also causes more solar radiation, giving rise to indoor overheating. Therefore, the atrium skylight is usually equipped with a shading system to prevent overheating and glare in summer. Yet again, excessive shading can reduce the indoor illuminance. When designing a skylight, it is necessary to take both the indoor cooling effect and the indoor illuminance into account. Common building shading systems include slatted shading, louvers and roller shutters [49] (Figure 6). Louver shading can protect building users from direct solar glare, and louvers are composed of multiple horizontal, vertical, or slanted slats of different shapes and surface finishes [50]. Louvers can be external or internal; they are used to partially or completely block the sun rays, and the size parameters of the shutters as well as the shading angle are controlled in studies [51,52]. Shading fabrics are widely used to shade exterior windows to improve visual and thermal comfort, control the amount of solar radiation, and enhance building interior privacy. The main optical properties characterizing sunshade fabrics are visible transmittance (VT) and coverage [53]. The specific design parameters of the shading system are shown in Table 6.

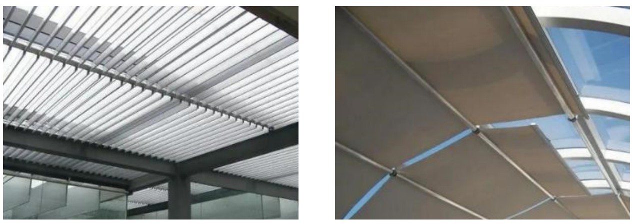

Figure 6. Louver and fabric shading.

Table 6. Shading system design parameter values.

Shading System Design Parameter	Value
Shade type	louver shade; fabric shade
Louver width (LW)	50–300 mm
Louver inclination (LI)	−60–60°
Fabric coverage (FC)	0.10–0.90
Fabric VT (FV)	0.10–0.90

3.3. Dynamic Daylight and Glare Evaluation Index

3.3.1. Dynamic Daylight Evaluation Index

With the development of research on architectural daylight, the traditional static daylight evaluation indicators have been unable to meet the design requirements of architectural daylight, and dynamic daylight evaluation has gradually become an important indicator of the quality of natural daylight in buildings. The dynamic daylight evaluation is mainly done by loading the typical climate data for the area where the research object is located throughout the year, constructing the Perez sky model, and simulating and calculating the building's annual (8760 h) daylight simulation, glare, and other daylight problems, so that the index can more truly reflect the natural daylight situation of the building throughout the year. Compared with the traditional static daylight evaluation index, dynamic daylight indexes based on climate-based daylight modeling can yield a building's year-round daylight performance. Climate-based daylight modeling (CBMD) allows for quantitative performance predictions based on local weather data. The resultant annual illuminance records are reduced to s comprehensive annual index [54].

The dynamic daylight evaluation index has been widely used in the recent research on daylight performance, such as DA, sDA, UDI, and ASE. The DA index was originally proposed by the Swiss Electric Association in 1989 and was further developed to measure the percentage of occupied hours [55]. UDI is defined as the illuminance falling in the range of 100–2000 lx [56]. Yu Bian et al. investigated the daylight performance index in Guangzhou, engaging in a comparative analysis of DA and DF, and compared the DA and DF values of four main facades of a side daylight room in Guangzhou through field measurements; they found that the actual tested DA and DF data deviated from the simulated values and concluded that DA was a more applicable daylight performance index than DF [57]. This annual daylight simulation evaluation index uses DA as well as sDA to evaluate the commercial atrium indoor daylight. On account of the high illuminance value and good daylight effect of the atrium, the sDA threshold can be set to 1000 lx, i.e., sDA1000, 50%, and the reference level of sDA is shown in Table 7.

Table 7. sDA rating evaluation.

sDA Level	Value
Inappropriate	<0.55
Acceptable	0.55–0.75
Satisfactory	>0.75

3.3.2. Glare Evaluation Index

Visual comfort is an important concern in interior daylight design, which is mainly related to sunlight intensity. People are more tolerant of uncomfortable glare from sunlight than from artificial lighting. The external window arrangement especially will affect the subjective impression of glare because daylight glare mainly comes from windows [58]. Regarding daylight glare, different glare indices have been proposed and analyzed, but the luminance-based terms and metrics using vertical illuminance are physically different and therefore cannot quantify daylight discomfort glare in the same way. Simulation methods have been developed and are able to quantify glare using existing evaluation metrics such as daylight glare probability [28], and currently common glare evaluation metrics include DGI, UGR, CGI, VCP, and DPG [53,58,59]. Among them, daylight glare probability or DGP is considered a reasonable index of the daylight discomfort glare, so the glare evaluation aspect of the dynamic evaluation index is evaluated by DGP. The concept of DGP, proposed in 2006 by Jan Wienold of Fraunhofer Institute for Solar Energy Systems (ISE) and Jens Christoffersen of Danish Building Research Institute (SBI), considers both the overall brightness of the field of view and the effects of glare and contrast [60,61].

Therefore, the glare evaluation index in this simulation study uses the discomfort glare probability (DGP), and the design outdoor illuminance is uniformly set to 50,000x. DGP is used to measure the glare index caused by daylight glare, and the rating evaluations of DGP is shown in Table 8. The equation is as follows [62]:

$$\mathrm{DGP} = 5.87 \times 10^{-5} + E_v + 9.18 \times 10^{-2} \log\left(1 + \sum_i \frac{L_{s,i}^2 \omega_{s,i}}{E_v^{1.87} P_i^2}\right)$$

where E_v is the vertical eye illuminance [lux]: Ls the luminance of source [cd/m^2]; ω_s is the solid angle of source; P is the position index.

Table 8. DGP glare rating evaluations.

DGP Level	Value
Imperceptible	<0.35
Perceptible	0.35–0.40
Disturbing	0.40–0.45
Intolerable	>0.45

3.4. Simulation Process

After determining the design parameters under study and the evaluation indexes for the simulation study, the next step is to bring the design parameter battery into Grasshopper and run the L + H (Ladybug + Honeybee) built-in daylight simulation engine to obtain different lighting indexes according to the 14 design parameters determined in the previous section grouped for simulation. This process was repeated until all single variables were analyzed, and the corresponding data were subsequently obtained (Figure 7).

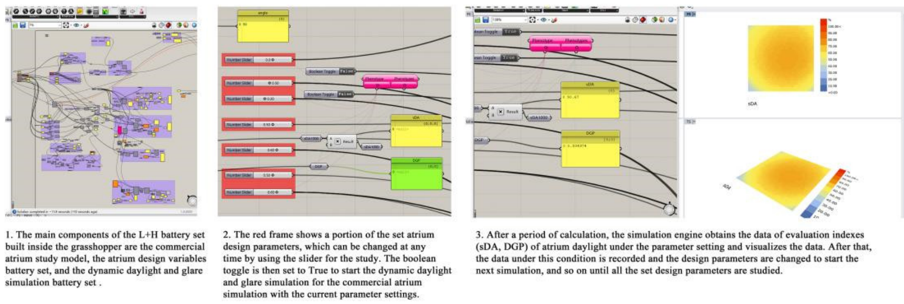

Figure 7. The simulation process diagram.

4. Results and Discussion

According to the three main types of design parameters selected (atrium design parameters, skylight design parameters, shading design parameters) (Tables 4–6), L + H (Ladybug + Honeybee) was used to simulate dynamic daylight and glare, and the corresponding daylight evaluation index data were obtained; then SPSS was used to analyze the correlation of each parameter.

4.1. Atrium Design Parameters Simulation

4.1.1. Atrium Size Simulation Analysis

In this section, the dimensions of the atrium are explored, and the length, width, height, and WI of the atrium are simulated separately for daylight simulation. The typical reference model is 30 m in length, 30 m in width, 15 m in height, and 0.5 in WI. Each parameter study only controls univariate for simulation, and the specific simulation process and results are as follows (Figures 8 and 9).

As can be seen from the line graph, the length, width, and height of the atrium size were not significantly correlated with sDA, and WI was significantly correlated with sDA; only the atrium length was not significantly correlated with DGP.

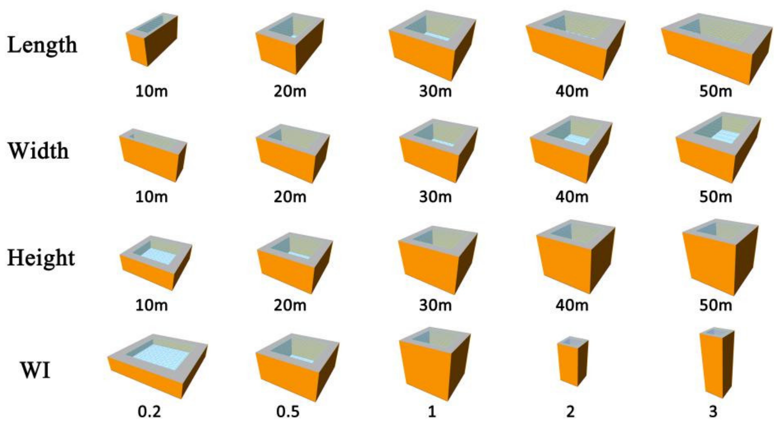

Figure 8. Atrium size diagram.

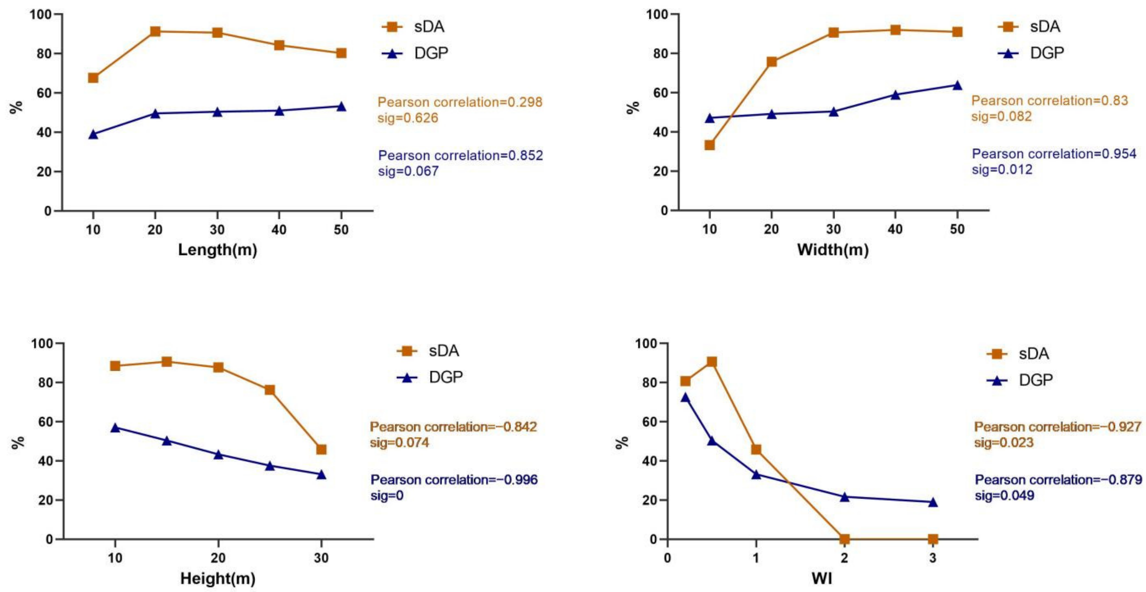

Figure 9. Simulation results for atrium size.

4.1.2. Atrium Inclination Simulation Analysis

In this section, the atrium profile inclination is explored, and the daylight simulation is performed for the atrium profile inclination variable. The atrium area is controlled to be the same, and the profile inclination angle is taken to be 60–120° and tested at 10° intervals (Figure 10); the simulation process and results are as follows (Figure 11).

As shown by the line graph, the atrium inclination angle was significantly correlated with both sDA and DGP.

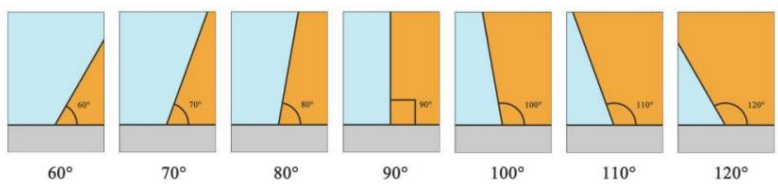

Figure 10. Atrium inclination inclination diagram.

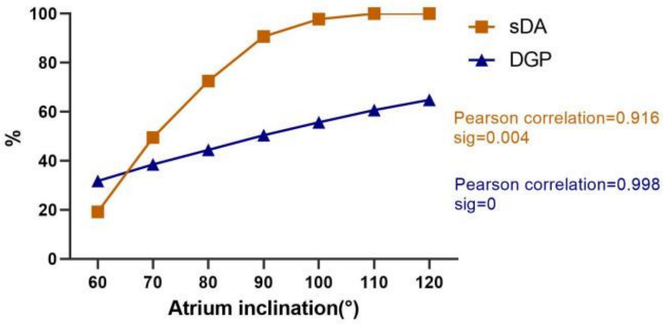

Figure 11. Simulation results of atrium inclination.

4.1.3. Indoor Reflectivity Simulation Analysis

In this section, the reflectance of the interior materials of the atrium is investigated, and the reflectance of the roof, walls, and floor of the atrium are simulated for daylight. The typical reference models of roof, wall, and floor reflectance are set to 0.8, 0.5, and 0.2, and each parameter is studied by controlling only a single variable for simulation (Figure 12).

From the line graph, it can be seen that all three reflectances are significantly correlated with the DGP, while only the roof reflectivity is not significantly correlated with the sDA, and the wall and floor reflectivities are significantly correlated with the sDA.

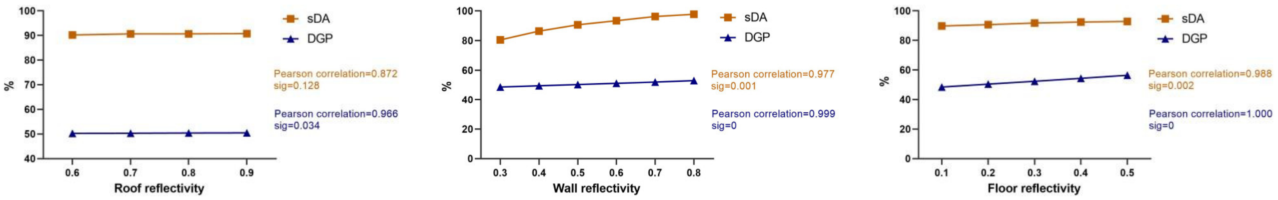

Figure 12. Simulation results of indoor reflectivity.

4.2. Skylight Design Parameters Simulation

4.2.1. Skylight Ratio Simulation Analysis

In this section, the skylight ratio is explored and tested at 0.1 intervals, and the specific simulation process and results are as follows (Figures 13 and 14).

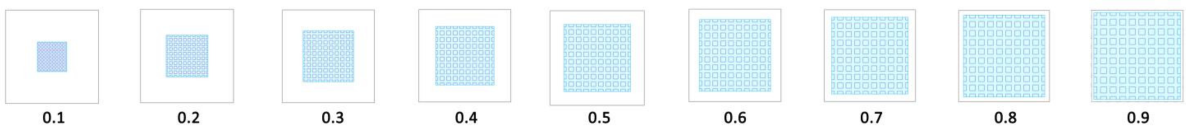

Figure 13. Skylight ratio diagram.

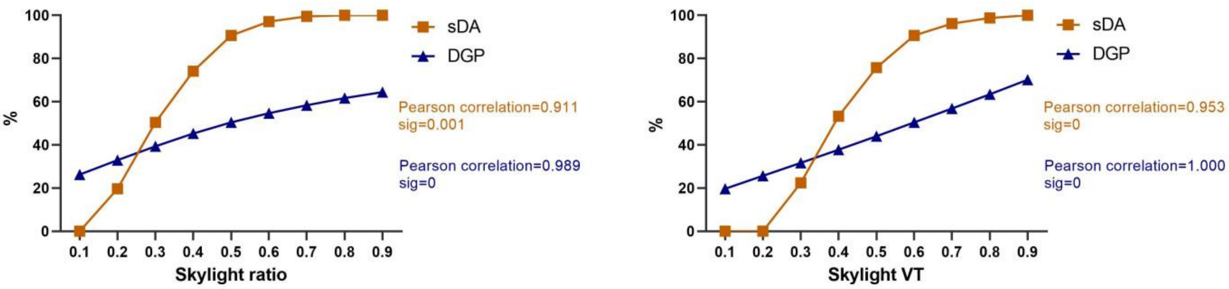

Figure 14. Simulation results of the skylight design parameters.

4.2.2. Skylight VT Simulation Analysis

In this section, the visible light transmittance of the skylight is explored and tested at 0.1 intervals, and the specific simulation process and results are as follows (Figure 13). The linear relationship between skylight VT and skylight ratio is similar, as shown by the line graph. Both design parameters are significantly correlated with sDA and DGP.

4.3. Shading System Design Parameters Simulation

4.3.1. Louver Width Simulation Analysis

This section explores the louver width in the louver shading system, where the typical reference model louver inclination is 90°, the louver width variable takes the range of 50–300 mm, and the test is conducted every 50 mm, and the specific simulation process is as follows (Figure 15).

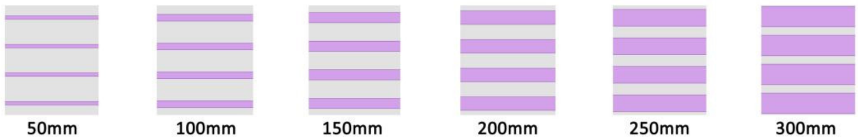

Figure 15. Louver width diagram.

4.3.2. Louver Inclination Simulation Analysis

This section explores the louver inclination in the louver shading system, in which the typical reference model louver width is 200 mm, the louver inclination variable takes the value range of 30–150° and is tested every 15°, and the specific simulation process and is as follows (Figure 16).

From the line graph (Figure 17), it can be seen that the relationship between louver inclination angle and sDA is parabolic and there is no significant linear correlation; thus, louver shading has difficulties in the subsequent study.

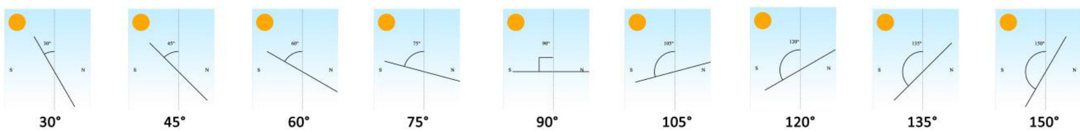

Figure 16. The louver inclination diagram.

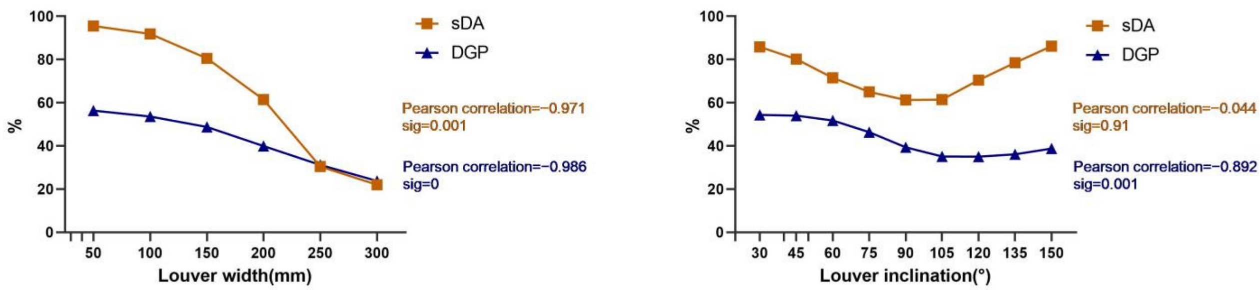

Figure 17. The simulation results of louver shading system.

4.3.3. Fabric Coverage Simulation Analysis

This section explores the fabric coverage in the fabric shading system, where the typical reference model fabric VT is 0.6 and the fabric coverage variable takes values in the range of 0.1–0.9 and is tested at 0.1 intervals, and the specific simulation process and results are as follows (Figures 18 and 19).

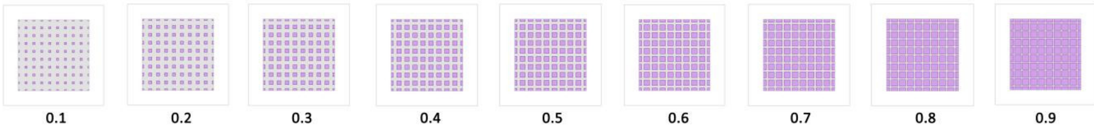

Figure 18. Fabric coverage diagram.

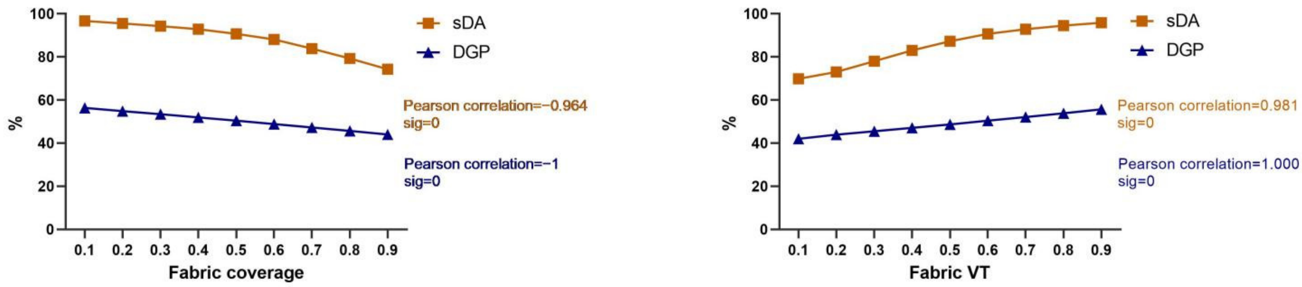

Figure 19. The simulation results for the fabric shading system.

4.3.4. Fabric VT Simulation Analysis

In this section, the visible light transmittance of the skylight is explored and tested at 0.1 intervals, and the specific simulation process and results are as follows (Figure 18). From the line graph, it is clear that the coverage of fabric shading is significantly correlated with VT with both sDA and DGP, so fabric shading is more suitable for the next orthogonal test as well as the sensitivity analysis than louver shading.

4.4. Sensitivity Analysis of Design Parameters

Sensitivity analysis can determine the most important parameters related to building performance, and the focus of the subsequent sustainable building design and optimization concentrate can be concentrated on this part of the design parameters. The adoption of sensitivity analysis in the early stage of design can improve the efficiency of building performance optimization [19,63]. Correlation analysis and multiple linear regression equations are commonly used data analysis methods, and the standardized regression coefficient (SRC) can provide the impact of architectural design parameters on indoor daylight. Ranking sensitivities of key parameters is also informative for design strategies. Combining an appropriate sensitivity program with building simulation software offers an effective and valuable tool for ranking the design parameters according to their importance for indoor daylight in a short time [64–67]. Paulo Filipe de Almeida Ferreira Tavares et al. utilized sensitivity analysis to consider the indoor thermal performance changes caused by different types of exterior walls, roofs, glazed windows, and shading, and to determine the degree of influence of each parameter [68]. Hangxin Li et al. proposed a method of multi-stage sensitivity analysis to identify the key design parameters for design optimization. The key building design parameters were subsequently optimized using a genetic algorithm to minimize the optimization objective [69]. Before the sensitivity analysis, the correlation analysis of each atrium design parameter was first conducted to screen out the design parameters with significant correlations on the atrium daylight quality (annual daylight and anti-glare level) for the subsequent study (Table 9).

The correlation analysis is carried out for each design parameter. After excluding the design parameter variables of no obvious significance, the result is that the fabric shading system was selected as the study object, and WI, Atrium inclination, Wall reflectivity, Floor reflectivity, Skylight ratio, Skylight VT, and fabric shading system parameter variables were obtained, where the WI parameter involved multivariate changes and affected the atrium area change so the WI variable was not considered; the following processes include a orthogonal experimental design using SPSS to carry out random sampling combination to obtain corresponding indicators of daylight, a multiple linear regression analysis to calculate the regression coefficient of each design parameter to analyze the degree of influence of the different design parameter variables on the annual daylight and glare in commercial buildings' atriums. A total of 81 sets of parameter combinations are obtained from the orthogonal design and are further processed by L + H (Ladybug + honeybee) to simulate annual daylight and glare in order to obtain the dependent variables sDA and DGP. The data will be brought into SPSS to calculate the results of the multiple linear regression equation:

$$Y = B_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_n X_n$$

B_0 is the constant term, β_1, β_2, β_3, ... , β_n is called Y corresponding to X_1, X_2, X_3, ... , X_n regression coefficient.

After the simulation, the data results were analyzed by multiple linear regression and the following results were obtained.

Table 9. Correlation analysis of atrium parameters. (AS = Atrium size; WI = Well index; AI = Atrium inclination; RR = Roof reflectivity; WR = Wall reflectivity; FR = Floor reflectivity; SR = Skylight ratio; SV = Skylight visible transmittance; LW = Louver width; LI = Louver inclination; FC = Fabric coverage; FV = Fabric visible transmittance), (* means that the sig. of the parameter with sDA and DGP are less than 0.05, i.e., significantly correlated).

Design Parameter			**sDA**		**DGP**	
			Pearson	**Sig.**	**Pearson**	**Sig.**
Atrium design parameter	AS	Length	0.298	0.626	0.852	0.067
		Width	0.830	0.082	0.954	0.012
		Height	−0.842	0.074	−0.996	0
		WI *	−0.927	0.023	−0.879	0.049
	AI	AI *	0.916	0.004	0.998	0
	IR	RR	0.872	0.128	0.966	0.034
		WR *	0.977	0.001	0.999	0
		FR *	0.988	0.002	1.000	0
Skylight design parameter	SR	SR *	0.911	0.001	0.989	0
	SV	SV *	0.953	0	1.000	0
Shading design parameter	Louver	LW *	−0.971	0.001	−0.986	0
		LI	−0.044	0.91	−0.892	0.001
	Fabric	FC *	−0.964	0	−1.000	0
		FV *	0.981	0	1.000	0

4.4.1. sDA Multiple Regression Equation

After the orthogonal test and the multiple linear regression calculation, the linear regression equation of sDA is:

$$Y = -114.907 + 0.902X_1 + 17.228X_2 - 11.448X_3 + 77.749X_4 + 90.823X_5 - 36.707X_6 + 13.739X_7$$

According to the analysis of the results of the following graphs (Tables 10 and 11; Figure 20), X_1 is Atrium inclination, X_4 is Skylight ratio, X_5 is Skylight VT, X_6 is Fabric coverage, and the sig of these variables are all less than 0.05, indicating that these parameters are significantly correlated in the regression equation. Meanwhile, X_2 is Wall reflectivity, X_3 is Floor reflectivity, and X_7 is Fabric VT, all of which have sig greater than 0.05, indicating that they are not significantly correlated in the regression equation; VIF < 5 indicates that there is no multicollinearity between the parameters. The model residuals, which basically obeyed a normal distribution, indicated that the error of this equation was within a reasonable range. Therefore, the linear regression equation established by the model is statistically significant.

SPSS software was used to fit the multiple linear regression and the coefficient of the model fit; $R^2 = 0.778$, indicating a good model fit, and DW = 2.117, indicating that there is no correlation between the independent variables in this model, i.e., a valid regression.

Table 10. The sDA multiple linear regression model.

Model	R	R Square	Adjusted R Square	Durbin-Watson	Sig.
sDA	0.882	0.778	0.757	2.117	0.000

Table 11. The sDA multiple linear regression equation analysis. (AI = Atrium inclination; WR = Wall reflectivity; FR = Floor reflectivity; SR = Skylight ratio; SV = Skylight visible transmittance; FC = Fabric coverage; FV = Fabric visible transmittance).

Model	Unstandardized Coefficients		Standardized Coefficients Beta	t	Sig.	Collinearity Statistics	
	B	Std. Error				Tolerance	VIF
(Constant)	−114.907	16.04		−7.164	0		
AI	0.902	0.114	0.436	7.913	0	1	1
WR	17.228	14.384	0.066	1.198	0.235	1	1
FR	−11.448	17.867	−0.035	−0.641	0.524	1	1
SR	77.749	9.097	0.471	8.546	0	1	1
SV	90.823	9.097	0.551	9.983	0	1	1
FC	−36.707	9.097	−0.223	−4.035	0	1	1
FV	13.739	9.097	0.083	1.51	0.135	1	1

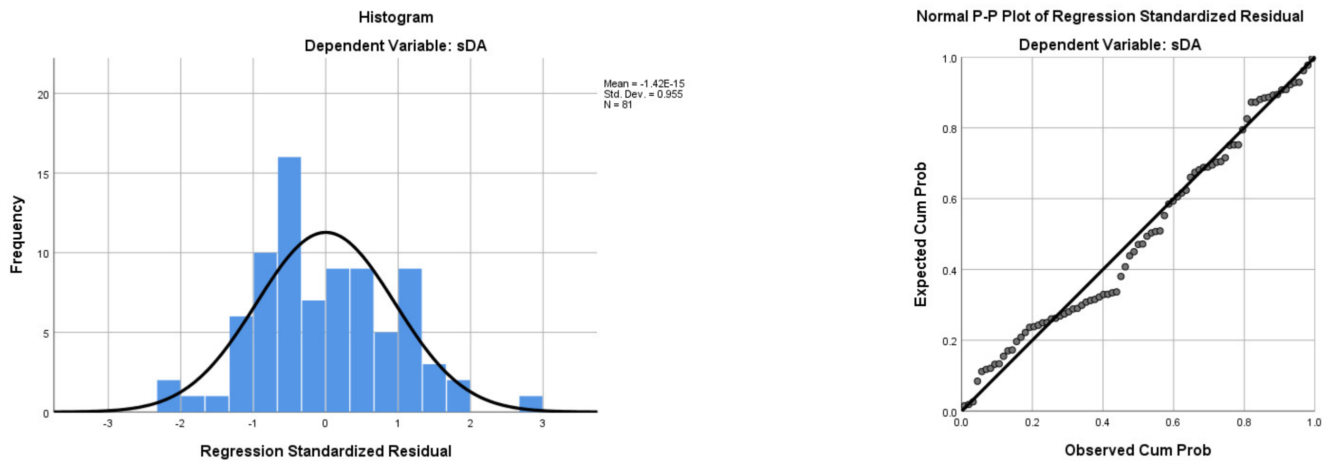

Figure 20. The sDA Histogram of the model's residual distribution and P-P diagram of the model's normalised residuals.

4.4.2. DGP Multiple Regression Equation

After the orthogonal test and the multiple linear regression calculation, the linear regression equation of DGP is:

$$Y = -31.332 + 0.36X_1 + 4.223X_2 - 2.808X_3 + 31.263X_4 + 48.024X_5 - 16.877X_6 + 12.954X_7$$

According to the analysis of the results of Tables 12 and 13 and Figure 21, these parameters sig are greater than 0.05, indicating that they are not significantly correlated in the regression equation; VIF < 5 indicates that there is no multicollinearity between the parameters. The model residuals, which basically obeyed normal distribution, indicated that the error of this equation was within a reasonable range. Therefore, the linear regression equation established by the model is statistically significant.

Table 12. The DGP multiple linear regression model.

Model	R	R Square	Adjusted R Square	Durbin-Watson	Sig.
DGP	0.934	0.872	0.860	2.156	0.000

Table 13. DGP multiple linear regression equation analysis. (AI = Atrium inclination; WR = Wall reflectivity; FR = Floor reflectivity; SR = Skylight ratio; SV = Skylight visible transmittance; FC = Fabric coverage; FV = Fabric visible transmittance).

Model	Unstandardized Coefficients		Standardized Coefficients Beta	t	Sig.	Collinearity Statistics	
	B	Std. Error				Tolerance	VIF
(Constant)	−31.332	5.34		−5.867	0		
AI	0.36	0.038	0.397	9.492	0	1	1
WR	4.223	4.789	0.037	0.882	0.381	1	1
FR	−2.808	5.948	−0.02	−0.472	0.638	1	1
SR	31.263	3.029	0.432	10.322	0	1	1
SV	48.024	3.029	0.663	15.856	0	1	1
FC	−16.877	3.029	−0.233	−5.572	0	1	1
FV	12.954	3.029	0.179	4.277	0	1	1

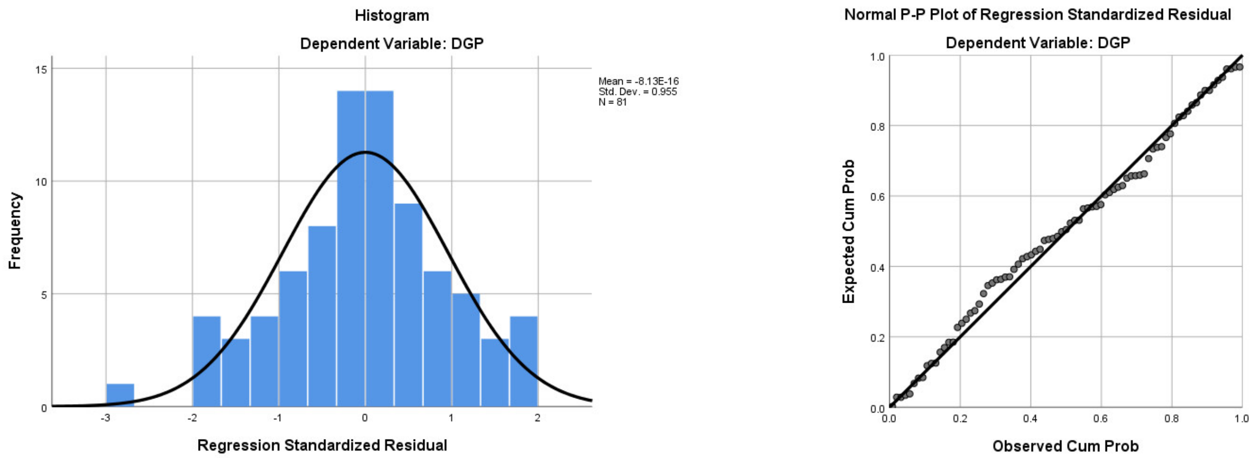

Figure 21. The DGP histogram of the model's residual distribution and the DGP P-P diagram of the model's normalized residuals.

SPSS software was used to fit the multiple linear regression and the coefficient of the model fit; $R^2 = 0.872$, indicating a good model fit, DW = 2.156, indicating that there is no correlation between the independent variables in this model, i.e., a valid regression.

4.4.3. Sensitivity Analysis of Atrium Design Parameters

After the sDA and DGP multiple linear regression analysis, the standardized coefficients beta of each design parameter was obtained, and then the degree of influence of each parameter on the target evaluation index can be seen, i.e., sensitivity analysis (Figure 22). From the figure, it can be seen that the most influential parameter on the atrium daylight is Skylight VT, followed by Skylight ratio, Atrium inclination, and Fabric coverage, while the remaining design parameters have less influence.

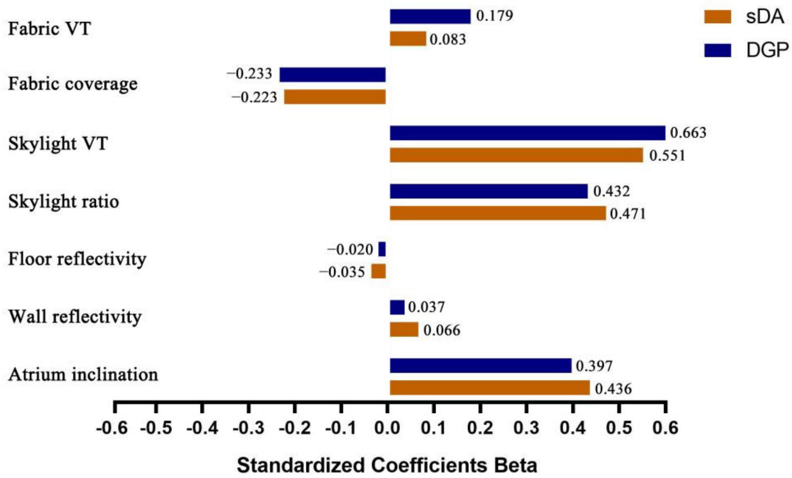

Figure 22. Sensitivity analysis of the atrium design parameters.

5. Multi-Objective Optimization of Daylight

Multi-objective optimization uses the optimization tool to calculate the optimal parameter combination and can greatly improve designers' efficiency and accuracy in building performance simulation. In the process of adopting a parametric daylight design, the computer is only used for the repetitive, heavy, and demanding calculations and analyses. The range of independent variables having been set before, the calculator can iteratively calculate by itself, so as to obtain the parameter combination indicative of the best effect of daylight [70,71]. To date, commonly used multi-objective computing methods include genetic algorithms, annealing algorithms, and evolutionary algorithms, such as Micro-GA, NSGA-II, MATLAB, Multiopt2, GenOpt, Galapagos, Octopus, and Wallace [72–74]. The Pareto frontier solution set is considered to be a trade-off solution among conflicting objectives in the design. Under the premise of multiple objectives, Pareto means that no objective can be improved to the detriment of other objectives [75,76]. Rizki A. Mangkuto et al. proposed a simulation study to explore the influence of WWR, wall reflectivity, and exterior window orientation on various daylight indicators and the daylight energy consumption of buildings in tropical climates, and they obtained the parity through a multi-objective optimization method and the Pareto frontier solution set [77]. Tarek Rakha et al. provided an optimization procedure with the goal of maximizing daylight uniformity by controlling the geometry of the ceiling [78]. Anxiao Zhang et al. introduced a study on the optimization of daylight energy consumption in school buildings in cold regions: The optimal solution was obtained through the use of Grasshopper to control building geometric parameters, the adoption of Ladybug and Honeybee to add building material properties, and the subsequent combination of energy consumption, daylight, and multi-objective optimization tools [23].

This research uses a novel parametric multi-objective optimization tool, Octopus, because it can achieve the multi-objective optimization in a more accurate and comprehensive way when setting the independent variables as the design parameters of the above sensitivity analysis and the dependent variables as sDA and DGP. The following processes include respective calculations of the maximum sDA and the minimum DGP to achieve the best effect of indoor daylight, the parameters of the genetic algorithm, and the final multi-objective optimization calculation (Table 14).

After thirteen iterations of Octopus, the computation is automatically stopped and the Pareto frontier solution set is obtained (Table 15, Figure 23). After the comparison of the results, among them, Group 3 and Group 4 have the best daylight effects, 90.89% and 88.56% of sDA and 37.67% and 39.63% of DGP, respectively, both meeting the maximum annual daylight effect and being lower than the DGP requirement of 0.4, and their corresponding design parameter combination can also be used as a reference.

Table 14. Octopus optimized parameter settings.

Optimization Parameters	Value
Elitism	0.7
Mut.Probablity	0.01
Mutation Rate	0.1
Crossover Rate	0.9
Population Size	20
Max Generation	20

Table 15. Pareto frontier solution. (AI = Atrium inclination; WR = Wall reflectivity; FR = Floor reflectivity; SR = Skylight ratio; SV = Skylight visible transmittance; FC = Fabric coverage; FV = Fabric visible transmittance).

Group	AI	WR	FR	SR	SV	FC	FV	sDA	DGP
1	117.00	0.34	0.30	0.69	0.29	0.58	0.39	70.11%	35.77%
2	117.00	0.31	0.17	0.69	0.36	0.75	0.41	81.78%	36.57%
3	119.00	0.60	0.17	0.68	0.30	0.51	0.39	90.89%	37.67%
4	91.00	0.65	0.27	0.89	0.37	0.50	0.13	88.56%	39.63%
5	118.00	0.60	0.36	0.68	0.30	0.50	0.39	91.00%	40.50%
6	118.00	0.60	0.17	0.84	0.30	0.76	0.76	100.00%	42.70%

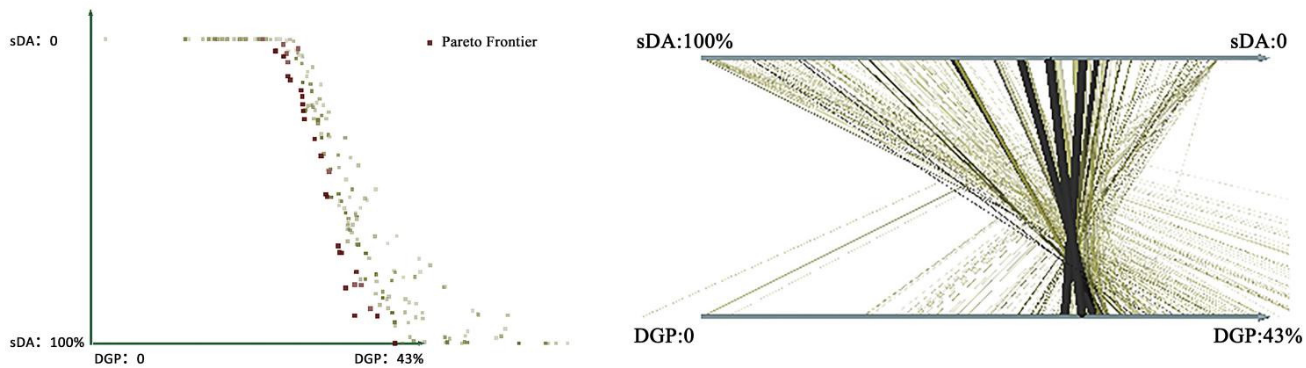

Figure 23. Pareto Frontier Images.

6. Conclusions

As the most common part of commercial buildings, the atrium design has a critical impact on the quality of natural daylight in the building interior. After simulation, correlation and linear regression analyses were performed on fourteen atrium design parameters to investigate the effect of each design parameter on the daylight quality of the commercial atrium. The results show that Skylight VT, Skylight ratio, Atrium inclination, and Fabric coverage have the greatest influence on atrium daylight quality, while the remaining parameters have a smaller degree of influence. The standardized regression coefficients of SV, SR, AI, and FC affecting atrium daylight are 0.551, 0.471, 0.436, and −0.223, respectively; the standardized regression coefficients affecting atrium glare are 0.663, 0.432, 0.397, and −0.233, respectively. The Pareto front solution set was obtained by filtering the results combined with the evaluation reference criteria. Among many results, the parameter combination with the best daylight and anti-glare effect reached 90.89% of sDA and 37.67% of DGP, which is obviously a satisfactory indoor daylight index for the atrium. Based on the parametric design, this study proposes a method for exploring the optimization of daylight in commercial atria in cold regions of China, which hopefully can provide some reference and ideas for future atrium daylight design.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su14137667/s1, File S1: Table Data.

Author Contributions: Conceptualization, Y.X.; Data curation, W.L.; Formal analysis, W.L.; Investigation, W.L.; Methodology, W.L.; Project administration, Y.X.; Supervision, Y.X.; Validation, Y.X.; Writing—original draft, W.L.; Writing—review & editing, Y.X. All authors have read and agreed to the published version of the manuscript.

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