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A Case Study on Multi-Objective Optimization Design of College Teaching Building Atrium in Cold Regions Based on Passive Concept

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Abstract: The atrium space represents one of the most energy-intensive areas within buildings. This is especially evident in college teaching buildings, where the inclusion of atriums often leads to increased energy consumption, primarily due to enhancements in lighting and thermal comfort. To address this issue, this study investigates atriums in cold regions within college teaching buildings and establishes four distinct atrium models for such buildings through typological abstraction and evolution. This study utilizes the Grasshopper (Ladybug Tools; developed by Robert McNeel & Assoc, Inc. in the United States.) parametric performance simulation platform to simulate daylight comfort and energy consumption within the atriums. Range analysis is subsequently applied to assess the impact of variables on energy consumption, and variables with the least influence are eliminated. Subsequently, the Octopus plug-in is employed to conduct multi-objective optimization for the four atrium types, resulting in the attainment of a Pareto-optimized solution set. Following optimization, the energy efficiency rates for the four atrium types are determined as 10.3%, 17.6%, 37.2%, and 30.5%, respectively, while the daylight comfort rates experience enhancements of 4.4%, 10.4%, 44.7%, and 34%, respectively. This study provides designers with a reference for optimizing design parameters during the early stages.

Keywords: multi-objective optimization; cold regions; atrium of college teaching buildings; passive concept; energy consumption; daylight comfort

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1. Introduction

With the rapid urbanization of China, environmental concerns stemming from energy consumption and carbon emissions have a significant impact on daily life [1]. As the scale and average energy intensity of public buildings continue to increase, the energy consumption of these structures has emerged as the largest component of overall building energy consumption in China, accounting for 33% of the total [2]. In response to this challenge, numerous measures have been proposed to enhance building performance, encompassing passive design, heating, ventilation, and air conditioning (HVAC), renewable energy, and energy management. Among these, passive design stands out as one of the most fundamental and effective approaches [3,4]. An exemplary passive building can substantially reduce energy consumption related to lighting and HVAC systems by minimizing cooling demands and lighting needs [5,6]. However, the inherent multi-objective and non-linear character of buildings makes it difficult to both reduce energy consumption and enhance the indoor physical environment [7].

Since the 1980s, extensive research on the "performance of building atriums" has been conducted, as documented in publications such as the "Skylight Handbook" [8] (1987) and "Design for Energy Conservation with Skylights" [9] (1981) by AMAA. These sources underscore the potential for daylight introduced through atrium skylights to reduce energy

consumption associated with lighting, cooling, and heating. In recent years, the growing importance of atrium design factors in relation to energy consumption and indoor environmental quality has introduced distinctive design challenges for architects [10]. Consequently, research pertaining to building atrium performance has experienced a gradual upsurge, with a predominant focus on atriums in office buildings [11–14], commercial structures [15,16], and hotel facilities [17,18]. However, there has been a relative dearth of studies addressing the performance of atriums in educational buildings, despite college teaching buildings representing a prominent category of public structures with considerable demands for thermal and daylight comfort [19].

In China, educational institutions account for 8% of the nation's total energy consumption, and students exhibit a per-person electricity consumption four times higher than the national average [20]. Air conditioning systems are indispensable for maintaining interior thermal comfort [21], and reconciling architectural design considerations to reduce atrium energy consumption while preserving atrium thermal comfort emerges as a critical challenge for the future [22]. Furthermore, the quality of daylight in educational buildings significantly impacts students' visual health [23], learning efficiency [24], and mood [25], emphasizing the imperative of optimizing interior spaces within teaching buildings. Previous research is shown in Table 1.

Table 1. A review of research methods and design parameters of the previous atrium research.

Year [Ref.]	Building Type	Design Parameter	Objective
2012 [26]	Unspecified	Atrium geometry (aspect ratio), surface reflectance	Daylight
2012 [23]	Office buildings	High-level opening sizes, wind speed, wall-to-roof void area, with and without roof overhangs above the clerestory	CFD
2013 [10]	Unspecified	Atrium geometry, atrium height, glass type, WWR	Daylight and Energy
2014 [17]	Solarium house	Radiance ambient parameters	Daylight
2015 [12]	Office buildings	Atrium height, skylight height to atrium height rate(h/H)	Daylight
2016 [18]	Multi-story apartment buildings	Shape factor, apartment floor area, WWR, skylight area and side window area, different regions	Energy
2017 [27]	Hotel buildings	Four atrium envelope and space characteristics of the designed alternatives, orientation	Energy
2017 [22]	Unspecified	SAR, case study, atrium's height, skylight size	CFD
2019 [28]	Unspecified	Atrium geometry, skylight area, building height	Daylight
2019 [29]	Office buildings	Roof-glazing size, atrium shapes, building height	CFD
2020 [30]	College school	Four main spaces considered	Viewing
2020 [25]	Office buildings	WWR, window area, shading equipment	Daylight and Energy
2021 [31]	Unspecified	Skylight Integrated Photovoltaic	Daylight
2021 [13]	Office buildings	Height, width, length (size), glazing ratio, reflectance	Daylight
2021 [32]	Library	AR, SAR	CFD
2022 [16]	Office building	Atrium structure design	Daylight
2022 [15]	Underground commercial spaces	The shape of atriums, profile inclination angle, the number of atriums, skylight height-to-width ratio	Daylight and Energy

Atriums have been gaining increasing popularity as a design space that harmoniously combines aesthetics, natural light, and an open atmosphere [10]. They function as an "intermediary space" with the capacity to regulate the indoor physical environment [33]. By implementing passive design strategies aimed at reducing HVAC and lighting energy consumption [34], skylights can enhance the thermal comfort within the atrium. Simultaneously, optimizing the building's architectural form can cater to diverse lighting requirements within the atrium [35]. Meanwhile, the atrium may significantly enhance the indoor physical environment. According to the "2021 Annual Development Research Report on Energy Efficiency in China's Buildings", lighting and thermal energy consumption account for the largest share of energy consumption in large public buildings, and all other energy consumption components are less energy intensive, less costly, and more easily

satisfied than those required to meet the light and thermal comfort requirements. Although numerous indoor environmental factors must be considered, the space design prioritizes the comfort of the light and thermal environment, particularly in cold places with extreme temperature fluctuations. Recognizing the interaction between light, thermal comfort, and atrium design considerations is the key to passively reducing the energy consumption of buildings.

In recent years, research on atrium design factors has predominantly concentrated on three key categories: building form factors, envelope and fenestration factors, and various other factors. In the realm of atrium building form factors, the parameters under scrutiny encompass atrium type [27,28,36], geometric shape [26,29,32], orientation, scale [37], and a host of other considerations (as outlined in Table 1). As for atrium envelope and fenestration factors, prior investigations have primarily emphasized key design elements such as the window-to-wall ratio [29,33], skylight-to-roof ratio [18], skylight shape and dimensions, as well as the thickness of exterior insulation panels [28], among other pertinent aspects. Furthermore, several additional elements, including geographic climatic conditions [38], spatial openness [30], and the integration of renewable energy sources [31], can exert a discernible influence on the performance of the atrium.

In summary, previous research on atrium design has not comprehensively addressed the optimization of design factors while accounting for multiple evaluation criteria. Notably, the impact of atrium design strategies on the indoor physical environment has not received adequate attention in the context of proposing optimal energy-efficient design strategies. Consequently, there is a pressing need to develop modeling and optimization methodologies for building performance that can effectively balance the objectives of reducing building energy consumption while concurrently enhancing the indoor physical environment [39].

This paper aims to address the issues of energy consumption and indoor light environment in atriums of college teaching buildings in cold regions by focusing on the optimal design of four types of atriums using various simulation software and data analysis platforms (Rhino version 6.7 and SPSS version 26) [40]. The innovative contribution of this study lies in proposing a correlation between multiple design factors for four types of atriums and their impact on energy performance and daylighting conditions in the cold region of China. Leveraging parametric performance simulation software (Grasshopper version 1.0.0007), a multi-objective optimization design process was executed for the atriums. Furthermore, a passive design approach tailored to the climatic characteristics of cold regions was developed.

2. Materials and Methods

This study is divided into three phases, including simulation parameter setting, orthogonal tests, and multi-objective optimization calculations. Figure 1 shows the research methodology and simulation process for the three different phases.

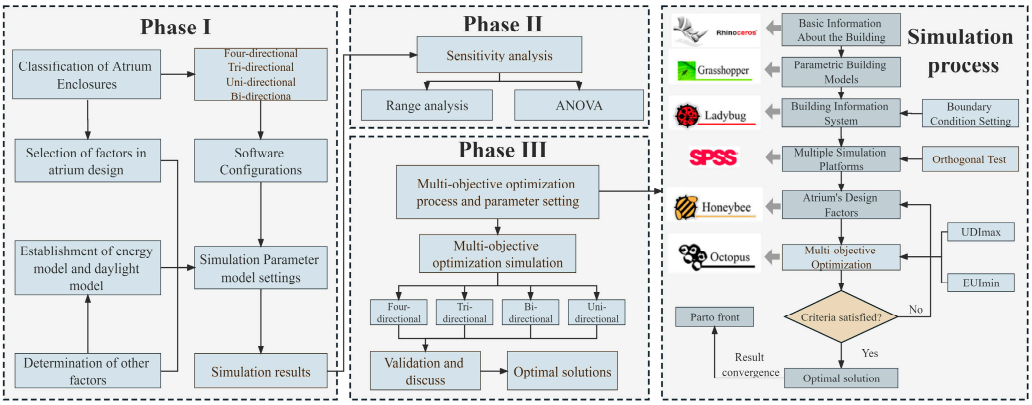


Figure 1. Overall research methodology.

The first phase is selecting a typical climate city, classifying and summarizing the forms and design factors of the atrium of teaching buildings, establishing the energy model and light environment model of the atrium of university teaching buildings, determining the evaluation indexes, and simulating the EUI and UDI of the model using the Honeybee and Ladybug plug-ins for Rhino and Grasshopper. The second phase involves using SPSS to create L_{32} (4^8) orthogonal test tables, conducting a sensitivity analysis of the atrium design factors affecting energy consumption, and analyzing the order of priority and significance of each design factor on energy consumption. The final phase is choosing energy consumption and daylight comfort as the optimization evaluation values based on the significance and sensitivity analysis of the orthogonal test. We performed simulations with the multi-objective optimization tool Octopus(Octopus was developed by the University of Applied Arts Vienna, Austria, and the German engineering firm Bollinger+Grohmann.) to obtain the optimal design solution sets for different types of atriums and explore the optimal design solution sets for various types of atriums.

2.1. Building Performance Simulation Software

With the rapid development of building performance simulation and optimization technology (Building Energy Simulation Optimization) [39], its applications have expanded and are now widely utilized in relevant research and practice areas. Grasshopper, a parametric plug-in based on Rhinoceros that unifies model development, performance simulation, and automated optimization search as a three-part BESO plug-in, is used in this research. Ladybug, Honeybee, Butterfly, and Dragonfly (Developed by MostaphaSadeghipour Roudsari, a visiting professor at the University of Pennsylvania, and Chris Mackey, an architect who graduated from the Massachusetts Institute of Technology.) are four modules that package a series of building physical equations like energy consumption, daylight, and ventilation into "operators", like batteries, for efficient simulation and analysis of building performance. Ladybug and Honeybee modules are utilized to analyze energy consumption and light environment in this research.

2.2. Setting Climate Conditions

In this research, a typical city selection is Jinan City, which belongs to the cold region of China and is influenced by solar radiation and atmospheric circulation, producing an environment with cold winters, hot summers, and uneven rainfall in all seasons. The year-round wind direction of this city is southwest and east, and the average annual temperature is 14.9 °C, with a minimum temperature of −11 °C and a maximum temperature of 37.2 °C. Therefore, the building design requires that it be insulated in the winter while taking heat protection into account in the summer [8]. This original measurement dataset was collected at Tsinghua University and the China Meteorological Administration. The climatic dataset file was loaded into the Ladybug Tools plug-in for Grasshopper to set the climatic parameter [41].

2.3. Basic Assumptions

Figure 2 classifies six categories of atriums based on previous research and a summary of atrium types [42,43]. It was found that Four-directional and Tri-directional atriums are the most numerous in college teaching buildings. Bi-directional and Uni-directional atriums are typically combined with building entrances and open spaces and are created primarily for visual comfort and spatial extension. Due to their rarity in teaching buildings, linear and distributed atriums are not the focus of this research.

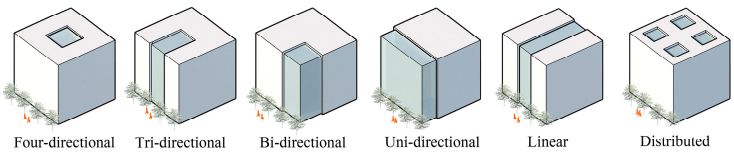


Figure 2. Summary of common types of the building atrium.

The building simulation model must be based on a large number of investigations and the evolution of typological abstraction, and it must be realistic in order for the study techniques and conclusions to have practical implications [15]. After extensive research based on the atriums of teaching buildings in cold regions, it was discovered that the majority of college teaching buildings are point-type, line-type, and enclosed-type. The depth and width of teaching buildings do not exceed 40 m, and the average number of floors is five or six. The area of the atrium mainly depends on the function and scale of the teaching building, which is about 200 m^2–400 m^2. The building has between three and six floors, and the height of each floor is mostly between 3.3 m and 3.9 m. Thus, it was decided to utilize the point-type teaching building as the base model. The base model was established as follows:

The Type I (Four-directional atrium) teaching building model simulates a three-story, four-sided, rectangular atrium form with 20 m length, 10 m width, and 9.9 m height, and the atrium is located in the center of the teaching building and surrounded by four interior surfaces; Type II (Tri-directional atrium) has the same size as Type I, but the atrium is located on the south side of the building, surrounded by three internal surfaces, and has one exterior surface; Type III (Bi-directional atrium) has the same size as Type I, but the atrium is located on the west–south side of the building, surrounded by two internal surfaces, and has two exterior surfaces; Type IV (Uni-directional atrium) has a different size teaching building as Type I, and the size is 20 m in length, 40 m in width, and 9.9 m in height. The atrium is located on the east side of the building, is surrounded by one internal surface, and has three exterior surfaces.

In addition, four base models have the same length-to-width ratio, height, skylight angle, window-to-wall ratio, and skylight-to-roof ratio. The model envelopes of the atrium, including all interior surfaces and floors, are considered "Adiabatic" (no heat exchange). Figure 3 shows the model of each type of atrium and teaching building for analysis and comparison.

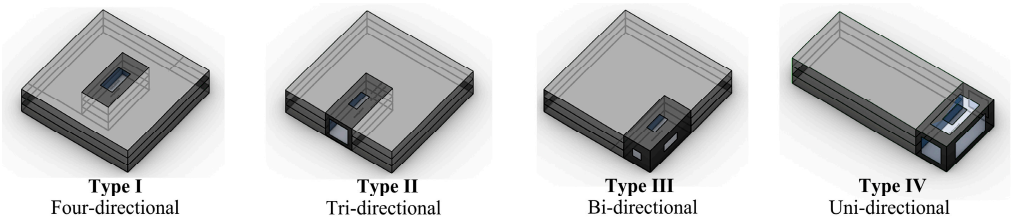


Figure 3. Base model of different types of atriums.

2.4. Factors Determination

2.4.1. Atrium Design Factors

As shown in Figure 4, the atrium's height is variable from 9.9 m to 12.6 m, and this range consists of four different heights (9.9 m, 10.8 m, 11.7 m, and 12.6 m). The orientation of the atrium determines the amount of solar radiation absorbed by the atrium and the performance of the indoor illumination in winter and summer. The orientation of the base model is 0°, 90°, 180°, and 270°, with four values representing the four directions: west, north, east, and south. Through investigation of the atrium of college teaching buildings, this study set the atrium's plan area to 200 m^2, and the base models' aspect ratios are set to 2.0, 1.65, 1.39, and 1.18, respectively. The skylight angle is selected as the parameter, and the skylight angle of the base model is set to 0°, 3°, 6°, and 9°, respectively.

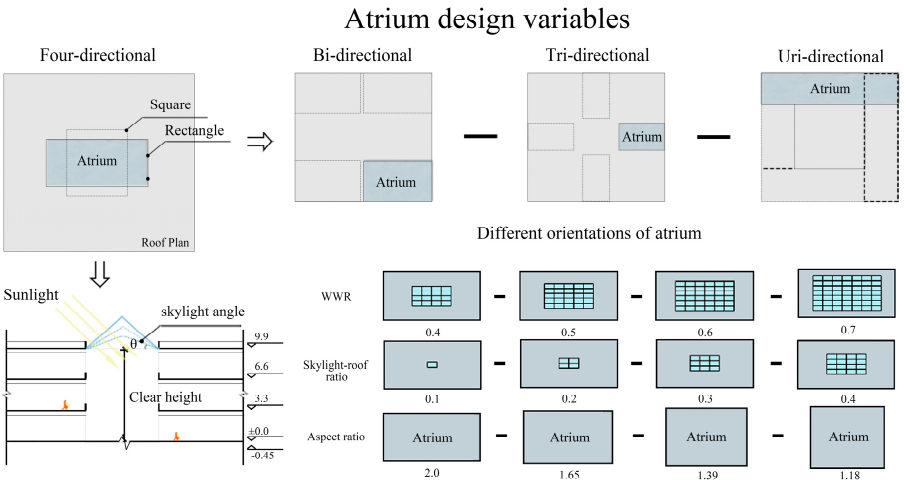


Figure 4. Atrium design variables setting.

The envelope is a dynamic regulating surface for the heat exchange between a building's interior and exterior areas, and its thermal performance determines the heat transmission and absorption to a certain extent [44]. Furthermore, the envelope-comprised building interface can effectively balance thermal comfort and energy consumption [45].

The opaque envelope is made up of external walls, roofs, and floors, and its thermal performance directly affects the level of heat exchange between the interior and exterior. The Heat Transfer Coefficient (U-value) of external walls and roofs can directly affect energy consumption. In this paper, the U-value of external walls and roofs' is referred to with reverent reference: external walls' U-value is set to 0.3 W/(m^2·K), 0.25 W/(m^2·K), 0.2 W/(m^2·K), and 0.15 W/(m^2·K), and the roofs' U-value is set to 0.25 W/(m^2·K), 0.2 W/(m^2·K), 0.15 W/(m^2·K), and 0.1 W/(m^2·K) [46]. Fenestration is mainly composed of windows and skylights that directly affect energy consumption in energy-efficient design and are usually expressed in terms of window-to-wall ratio [47]. Therefore, the atrium window-to-wall ratio (WWR) and the skylight-to-roof area ratio (SRR) are set according to the above criteria. The window-to-wall ratio is set at 0.4, 0.5, 0.6, and 0.7, and the skylight-to-roof area ratio is set at 0.1, 0.2, 0.3, and 0.4. The atrium design factors and levels are shown in Table 2.

Table 2. Design factors and level settings.

Design Factors	Level	1	2	3	4
Building form	A: Atrium's skylight angle (°)	0°	3°	6°	9°
	B: Atrium's orientation (°)	0°	90°	180°	270°
	C: Atrium's plane aspect ratio	2.0	1.65	1.39	1.18
	D: Atrium's height (m)	9.9	10.8	11.7	12.6
Fenestration	E: WWR	0.4	0.5	0.6	0.7
	F: SRR	0.1	0.2	0.3	0.4
Opaque envelope	G: External walls' U-value [W/(m^2·K)]	0.3	0.25	0.2	0.15
	H: Roofs' U-value [W/(m^2·K)]	0.25	0.2	0.15	0.1

2.4.2. Other Factors

In addition, other factors affecting energy consumption and the daylight environment also need to be considered, according to the relevant references [48–50], including enclosure parameters, indoor load parameters, HVAC, and ACH, as shown in Table 3.

Table 3. Atrium energy model envelope, indoor load, and HAVC system parameter settings.

Model		Structure	Input Value
Enclosure parameters	Wall construction	Brick	0.3, 0.25, 0.2, 0.15 W/(m^2·K)
	Roof construction	Concrete	0.25, 0.2, 0.15, 0.1 W/(m^2·K)
	Floor construction	Adiabatic floor	-
	Glazing	5low-E + 12Air + 5	U-value: 1.8 W/(m^2·K), SHGC: 0.4, VT: 0.6
	Skylight	5low-E + 12Air + 5	U-value: 1.8 W/(m^2·K), SHGC: 0.4, VT: 0.6
Indoor load parameters	People density	-	0.3 ppl/m^2
	Lighting density	-	9 W/m^2
HVAC	HVAC system	Ideal air loads system	-
	Cooling set point	-	28 °C
	Heating set point	-	18 °C
ACH	Air changes per hour	-	4 times/h

2.5. Evaluation Indicators Determination

After setting the model and determining the variables, it is also required to define the evaluation value of the optimization objective—also known as the evaluation indices. In this article, the EUI (kWh/m^2) is utilized throughout the year to compare and evaluate the energy consumption of atriums in teaching buildings.

Spatial Daylight Autonomy (sDA) and Useful Daylight Illuminance (UDI) as dynamic evaluation indices have been widely used internationally in recent years to evaluate the daylight performance of building spaces [51,52]. The UDI index evaluates the impact of daylight on human comfort based on the minimum and maximum critical values of horizontal surface illuminance, which reflect the illuminance interval that meets human light comfort [53,54]. As a single evaluation index, UDI is more adaptable to light comfort than sDA, making it excellent for evaluating building design factors. UDI lacks a uniform standard and a consistent illuminance threshold value [55]. People may be able to endure lower natural illuminance levels due to the use of various electronic auxiliary devices [56,57]. Therefore, this study will use the UDI value as the evaluation index, with minimum and maximum critical values of 100 lux and 2000 lux, respectively [58].

2.6. Establishment of the Orthogonal Test

As shown in Table 2, the atrium design factors and levels were calculated after determining the base model and relevant parameters. If a full-scale experiment is conducted by arranging and combining all design factors and levels, the time cost of utilizing simulation software is higher, and the effort is heavier. Compared to full-scale experiments, orthogonal tests are an efficient technique to reduce the number of trials using a scientific process, and the main idea is to choose representative samples from the full-scale experimental combinations according to certain rules [59]. Table 4 shows the L_{32} (4^8) orthogonal test that was prepared by the statistical analysis software SPSS (Version 22.0) using four-level variables for each design factor.

Table 4. L_{32} (4^8) orthogonal test table.

Number	A	B	C	D	E	F	G	H
1	0°	0°	2.0	9.9	0.4	0.1	0.2	0.2
2	0°	0°	1.65	10.8	0.7	0.4	0.4	0.3
3	0°	3°	1.39	12.6	0.4	0.2	0.4	0.35
				.....				
30	9°	180°	1.65	9.9	0.7	0.3	0.3	0.2
31	9°	270°	1.39	11.7	0.4	0.1	0.3	0.25
32	9°	270°	1.18	12.6	0.7	0.4	0.5	0.35

2.7. Multi-Objective Optimization

Recently, research on the use of performance simulation software to assist architects in optimization design has been increasing. By using multi-objective optimization, the relationship between passive design methods and evaluation indices is investigated. The objective functions are developed in line with the main objective of the study, which is to reduce energy consumption in a cost-effective manner and enhance the daylight environment of the atrium. The most widely used algorithm based on the Pareto dominance approach refers to the use of Pareto optimal solutions, where any two solution sets satisfy:

$$\begin{array}{l} \forall i \in \{1, 2, \ldots, Z\}, f_i(X_1) \leq f_i(X_2) \\ \exists j \in \{1, 2, \ldots, Z\}, f_i(X_1) \leq f_i(X_2) \end{array} \quad (1)$$

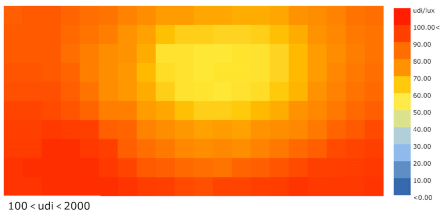
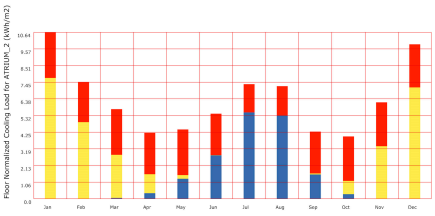
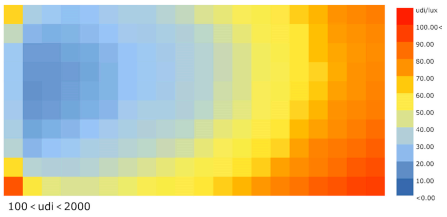
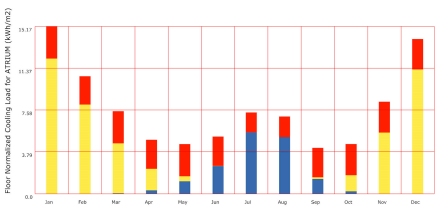
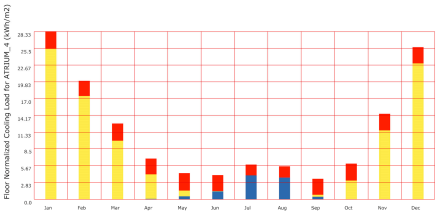
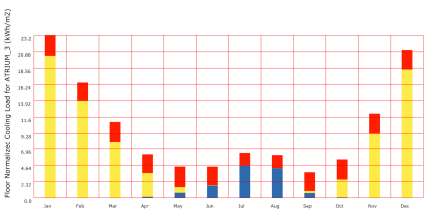
where Z is the number of objectives and fi is the sub-objective. X_2 is called a non-dominated solution if all X_1 sub-objectives are not inferior to X_2 and at least one objective in the solution X_1 is superior to X_2; if X_1 is not dominated by all solutions in the solution set, X_1 is called a Pareto optimal solution.

3. Results and Analyses

3.1. Base Model Energy and Daylight Simulation Results

The EUI and UDI of the base model are simulated. The diagram and data are obtained as shown in Table 5.

Table 5. Values and diagram of UDI and EUI of base model for the atrium.

Atrium Type	$UDI_{100\sim2000\ lux}$(%)	EUI (kWh/m^2)
Four-directional (Type I)	 80.7	 61.5
Tri-directional (Type II)	 80.1	 75.3
Bi-directional (Type III)	 42.7	 90.6
Uni-directional (Type IV)	 33.9	 90.3

3.2. Orthogonal Test

The combination schemes of the orthogonal test table were entered into Grasshopper, and the 32 design factor schemes in the orthogonal test table were simulated in succession to derive the EUI for each combination scheme. The results were then loaded into SPSS Version 26 to analyze the effect of atrium design factors on energy consumption. After exporting the results of the analysis, it is essential to do a sensitivity analysis. Firstly, range analysis is used to determine the order of atrium design aspects that impact building energy consumption. Then, the trend and ideal parameter combinations of each component that influences building energy consumption are analyzed. Secondly, ANOVA was used to determine the significance of atrium design parameters on the atrium's energy consumption.

3.2.1. Range Analysis

The range analysis can reflect the degree of influence of each factor on the orthogonal test results. The higher the range difference, the larger the effect of atrium design factors on results and findings, i.e., the greater the change in energy consumption. Table 6 shows the results of orthogonal tests with four types of atriums.

Table 6. Results of the orthogonal test calculation R-value.

Atrium's type	A	B	C	D	E	F	G	H
Type I	0.69	0.51	0.29	1.44	0.22	22.96	0.39	4.52
Type II	0.59	6.05	4.63	4.73	9.58	19.32	3.13	6.46
Type III	6.3	7.89	4.4	13.27	21.75	14.52	5.63	4.01
Type IV	4.29	3.25	4.19	7.42	27.32	11.63	3.88	3.86

According to Table 6, the effects of each design factor on energy consumption within the provided limits are as follows for four types of atriums: Four-directional atrium: F > H > D > A > G > C > B > E; Tri-directional atrium: F > E > H > B > D > C > G > A; Bi-directional atrium: E > F > D > B > A > G > C > H; Uni-directional atrium: E > F > D > A > C > G > H > B. It can be seen that when different atrium types are used in teaching buildings, each design factor has a different effect on the atrium's energy consumption.

Figure 5 illustrates that the order of design factors affecting energy consumption has been changing for different types of atriums. It is observed that the order of priority is gradually increasing for E (WWR), indicating that the degree of influence of this factor is greater as the atrium has more exterior surfaces. The order of design factors is gradually decreasing for F (SRR), indicating that the degree of influence of this factor is lower as the atrium has more exterior surfaces. The order of priority fluctuates for A (atrium's skylight angle), B (atrium's orientation), C (atrium's aspect ratio), D (atrium's height), G (walls' U-value), and H (roofs' U-value). This shows that the fenestration has the greatest influence on energy consumption, followed by the building form.

Figure 6 shows the effects of design factors on the four types of atriums (Four-directional, Tri-directional, Bi-directional, and Uni-directional) on the EUI. For the Four-directional atrium (Type I), by changing the atrium's orientation, EUI tends to rise and then fall; by decreasing the atrium's aspect ratio, EUI tends to rise and then fall; and by changing factors, including the atrium's height, roofs' U-value, and SRR, EUI tends to rise continuously. When the SRR is 0.4 and the roofs' U-value is 0.25 W/(m^2·K), the maximum and minimum EUI values are approximately 76 and 61.9 kWh/m^2, respectively. The remaining factors have nearly no effect on the EUI because the Four-directional atrium has no contact with the envelope's outside surface. The effects of WWR and wall thickness on the EUI are negligible.

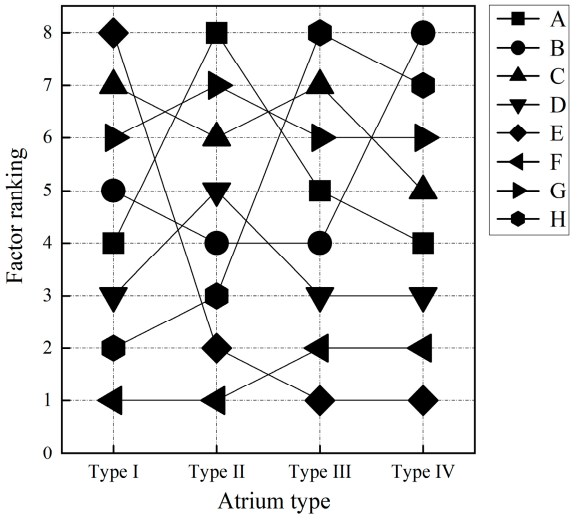


Figure 5. The order of influence of atrium design factors on energy consumption.

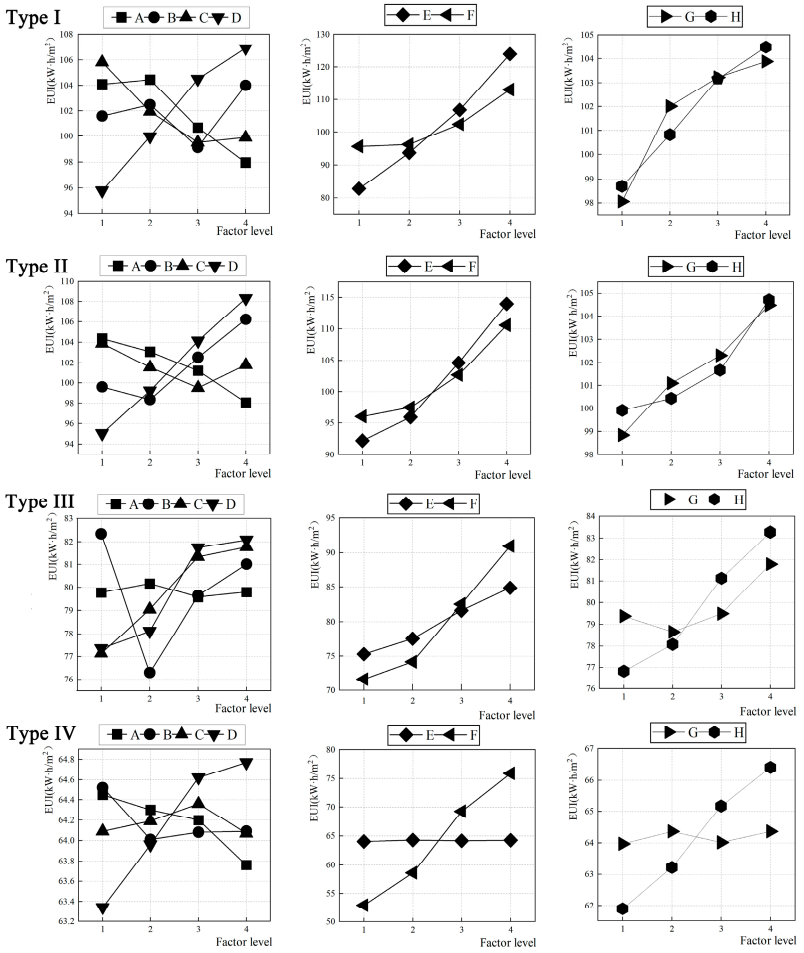


Figure 6. Line chart of the effect of different design factors on EUI.

For the Tri-directional atrium (Type II), by increasing the atrium's skylight angle, the EUI fluctuates; by changing the walls' U-value and increasing the atrium's orientation, the EUI falls and then rises; and by changing the remaining factors, including the atrium's height, the atrium's aspect ratio, WWR, SRR, and the roofs' U-value, the EUI tends to rise continuously. When the SRR is between 0.1 and 0.4, the maximum and minimum EUI values are around 72.3 and 92.1 kWh/m^2, respectively.

For the Bi-directional atrium (Type III) and the Uni-directional atrium (Type IV), both types of atriums' EUI tend to rise with an increase in envelope factors. When the WWR is 0.4 and 0.7, the maximum and minimum EUI values of Bi-directional atrium are approximately 92.5 and 114.5 kWh/m^2, and the EUI values of Uni-directional atrium are about 83.5 and 126.4 kWh/m^2.

3.2.2. Variance Analysis

Range analysis illustrates the order of influence of each atrium design factor on energy consumption but does not consider whether the effect of each factor action on the test results is significant [59], necessitating additional ANOVA on the test results to identify the factors that significantly influence the atrium's energy consumption. SPSS (version 22) is used to perform ANOVA on the orthogonal test data. The results of the ANOVA in four types of atriums are presented in Table 7.

Table 7. Four types of atrium ANOVA results.

	Atrium Design Factor	F	*p*		Atrium Design Factor	F	*p*
Type I	A. Skylight angle	0.27	0.845	Type III	A. Skylight angle	12.608	0.003 **
	B. Orientation	0.167	0.915		B. Orientation	20.738	0.001 **
	C. Plane aspect ratio	0.055	0.982		C. Plane aspect ratio	5.446	0.030 *
	D. Height	1.331	0.339		D. Height	56.213	0.000 **
	E. WWR	0.029	0.993		E. WWR	158.408	0.000 **
	F. SRR	327.375	0.000 **		F. SRR	72.445	0.000 **
	G. External walls' U-value	0.138	0.934		G. External walls' U-value	9.295	0.008 **
	H. Roofs' U-value	12.35	0.003 **		H. Roofs' U-value	7.81	0.012 *
Type II	A. Skylight angle	0.143	0.931	Type IV	A. Skylight angle	3.453	0.08
	B. Orientation	15.677	0.002 **		B. Orientation	1.54	0.287
	C. Plane aspect ratio	10.756	0.005 **		C. Plane aspect ratio	3.078	0.1
	D. Height	13.799	0.003 **		D. Height	8.997	0.008 **
	E. WWR	42.09	0.000 **		E. WWR	115.591	0.000 **
	F. SRR	178.277	0.000 **		F. SRR	24.238	0.000 **
	G. External walls' U-value	4.252	0.052		G. External walls' U-value	2.507	0.143
	H. Roofs' U-value	19.911	0.001 **		H. Roofs' U-value	2.42	0.151

F is a value to compare the variance and determine if the effect of factors on dataset variation is significant or not; *p* is a value to test whether the effect of factors in the ANOVA on the change in data is significant; "*" or "**" indicates that the ***p*** reaches the 0.05 level and 0.01 level of significance.

3.3. Multi-Objective Optimization Simulation Results

The results of the optimal solution are compared to the base model to determine the corresponding improvement in EUI and $UDI_{100\sim2000\,lux}$. Based on a sensitivity analysis of the atrium energy consumption under the orthogonal test, design factors that affect the end position of energy consumption are screened, and the design factors of the wall's U-value and roof's U-value are removed in the subsequent analysis, and the optimal combination of design factors is obtained (as shown in Table 8).

Table 8. Design factors screening for different types of atrium design.

Atrium's Type	Design Factor Ranking	A	B	C	D	E	F	G	H
Type I	F > H > D > A > G > C > B > E	√	√	√	√	×	√	×	×
Type II	F > E > H > B > D > C > G > A	×	√	√	√	√	√	×	×
Type III	E > F > D > B > A > G > C > H	√	√	√	√	√	√	×	×
Type IV	E > F > D > A > C > G > H > B	√	×	√	√	√	√	×	×

After screening the design factors, the multi-objective optimization module Octopus in Grasshopper effectively invokes the independent variable control module and the target module and calculates the cyclic optimization search with the assistance of a simulation platform for optimal optimization. Figure 7 shows that the atrium design parameters can form a controlled slider interface within the plug-in, and the target values derived from the EnergyPlus calculation engine and Daysim calculation engine (EnergyPlus is a building energy simulation engine developed by the U.S. Department of Energy (DOE) and Lawrence Berkeley National Laboratory (LBNL). Daysim is a simulation software developed by the Canadian Institute of Construction Research specifically designed to predict the year-round natural daylighting performance of buildings.) are also connected to the Octopus module, with the design variables set on the left side and evaluation indicators set on the right side of the plug-in. Octopus-based simulation calculations are performed, where the number of solutions per generation is set to 50 for a total of 30 generations, with a total of 1500 solutions evaluated.

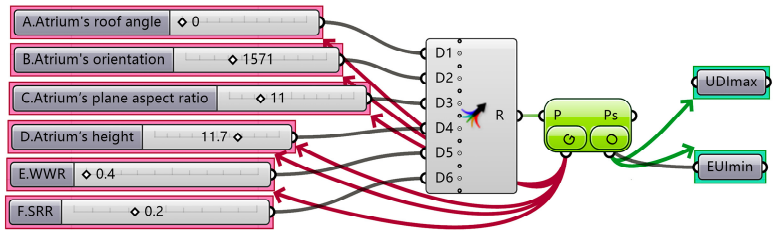
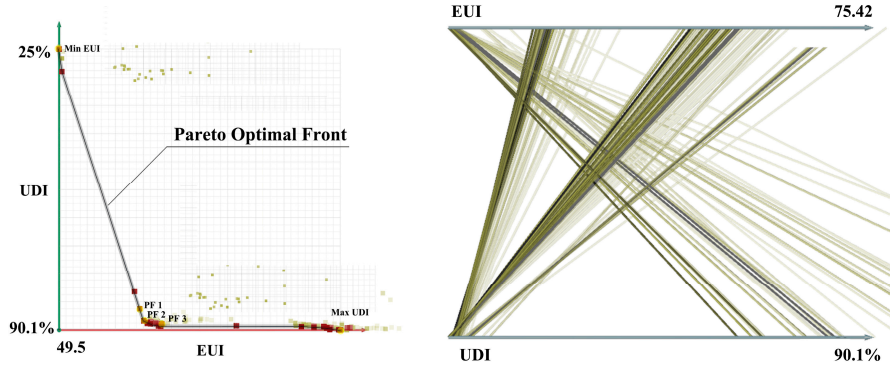


Figure 7. Octopus plug-in.

3.3.1. Four-Directional Atrium

Figure 8 shows the Pareto front chart formed by a multi-objective simulation of the Four-directional atrium, where the two axes represent EUI on the X-axis and $UDI_{100\sim2000\ lux}$ on the Y-axis, respectively. After many cycles of updating, the Pareto front curve (ideal solution set) is created, and the comparatively acceptable solution set is positioned near the Pareto curve, with the closest relative location to the far point being chosen. Three points are chosen and set as representatives of the Pareto optimal solution set, while the parameter values of Min EUI and Max UDI in the curve are chosen, and a total of five goal values are taken for comparison and analysis. The data are displayed in Tables 9 and 10.



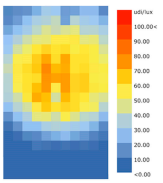
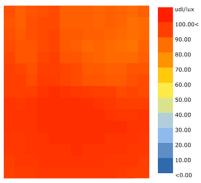
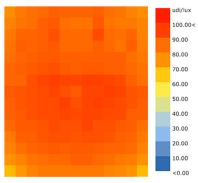
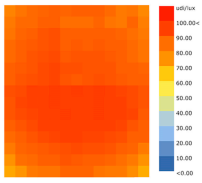
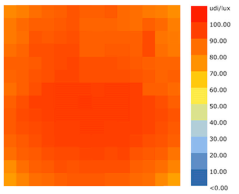
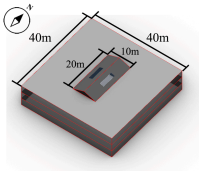
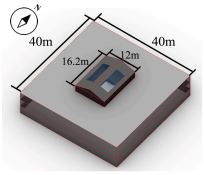
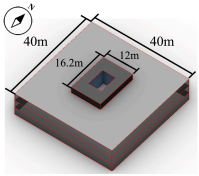
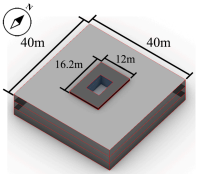
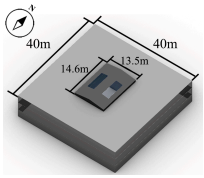
(**a**) (**b**)

Figure 8. (**a**) Pareto frontier for Four-directional atrium; (**b**) Multi-objective sets for Four-directional atrium.

Table 9. The objective value of each type of solution is set in the Four-directional atrium.

Atrium Target Value	Min EUI	Max UDI	Pareto Set 1	Pareto Set 2	Pareto Set 3
EUI (kWh/m^2)	49.5	68.4	55.2	55.6	56.4
$UDI_{100\sim2000\ lux}$(%)	29.6	89.6	82.6	84.5	85.2

Table 10. Design parameters for various types of solutions are set in the Four-directional atrium.

Solution Set	Min EUI	Max UDI	Pareto Set 1	Pareto Set 2	Pareto Set 3
UDI Map					
Model					

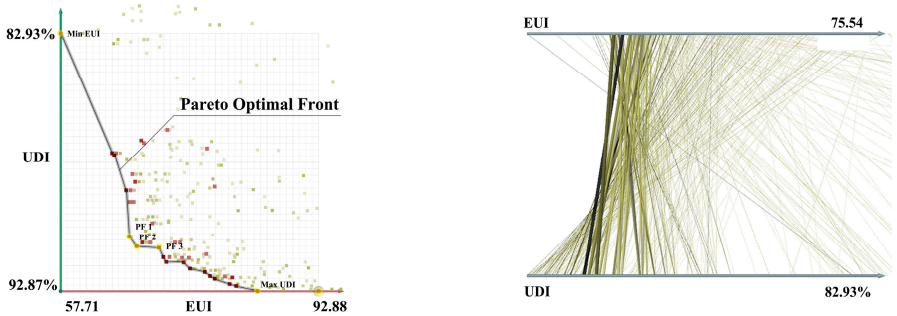
The majority of Pareto's optimal solutions appear close to the X-axis in the Pareto Frontier diagram. This indicates that the overall level of $UDI_{100\sim2000\,lux}$ is high in the Four-directional atrium, as is the lighting efficiency, with the EUI distribution ranging from 49.5 to 68.4 kWh/m^2 with a large difference. Therefore, the optimization of the Four-directional atrium should be based on energy consumption optimization, and the solution set should be chosen as close as feasible to the X-axis.

To validate the accuracy of the calculation results, Pareto sets 1 and 2 have identical target values except for the atrium's height, which corresponds to the design factors. In the meantime, three relatively distant solution sets of Pareto set 1, Min EUI, and Max UDI are chosen, and there are further discrepancies related to the design factors to validate the accuracy of the calculation results.

When EUI < 55 kWh/m2, UDI for the Four-way atrium decreases; when UDI is between 85% and 89%, EUI increases substantially; when UDI is 89.6%, EUI is 68.4 kWh/m^2. Therefore, the solution set of 57 > EUI $\geq$ 55 kWh/m^2 should be selected, and the Pareto preferred solution is ideal for maximizing energy savings by appropriately reducing the quality of daylight. Table 10 depicts the parameter combinations and UDI maps of five types of solution set for the Four-directional atrium. It can be seen that Pareto sets 1, 3, and Max UDI have superior and more equally distributed indoor daylight uniformity.

3.3.2. Tri-Directional Atrium

Referring to the method described in Section 3.3.1, a multi-objective simulation calculation was performed for the Tri-directional atrium to generalize the Pareto front solutions in Figure 9. The settings for Min EUI and Max UDI were also selected, with five target values, and the results are displayed in Tables 11 and 12.



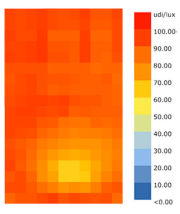
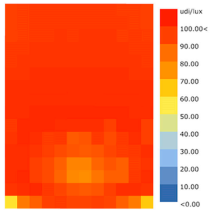
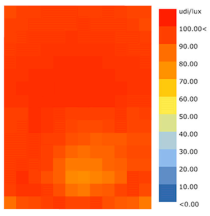
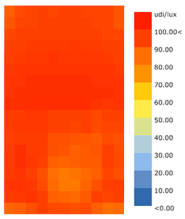
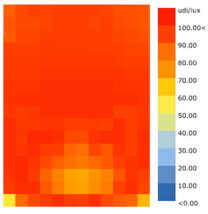
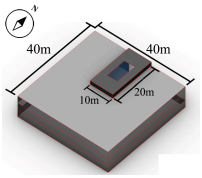
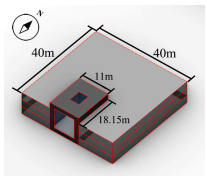
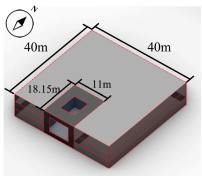
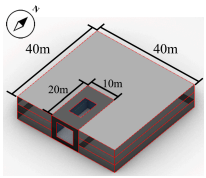
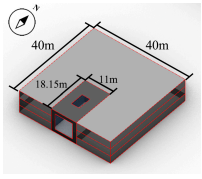
(**a**) (**b**)

Figure 9. (**a**) Pareto frontier for Tri-directional atrium; (**b**) Multi-objective sets for Tri-directional atrium.

Table 11. The objective value of each type of solution is set in the Tri-directional atrium.

Atrium Target Value	Min EUI	Max UDI	Pareto Set 1	Pareto Set 2	Pareto Set 3
EUI (kWh/m^2)	57.7	71.3	62.5	63	64.5
$UDI_{100\sim2000\ lux}$(%)	82.9	92.9	90.5	90.2	90.1

Table 12. Design parameters for various types of solutions set in the Tri-directional atrium.

Solution Set	Min EUI	Max UDI	Pareto Set 1	Pareto Set 2	Pareto Set 3
UDI Map					
Model					

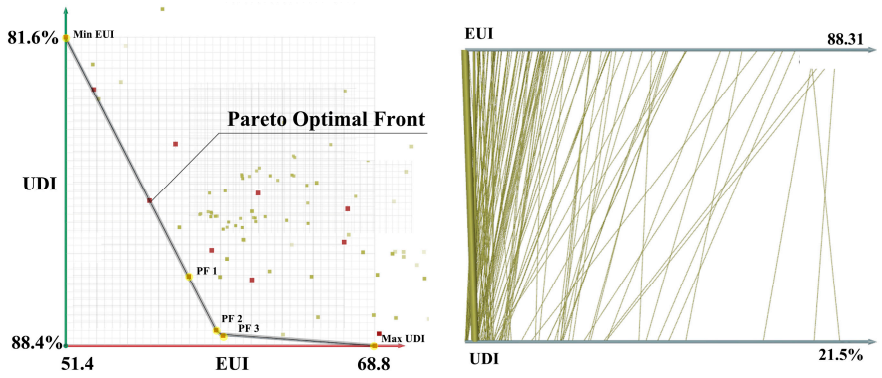
From the Pareto Frontier diagram, it can be seen that the Pareto curve is more equally distributed, with the majority of solution sets distributed near the X-axis, indicating that the overall level of UDI in the Tri-directional atrium is high, with UDI ranging from 82.9% to 92.9%. EUI varies significantly from 57.7 to 71.3 kWh/m^2, representing a wide variation. Therefore, the design optimization of the Tri-directional atrium must emphasize the optimization of energy consumption and daylight comfort.

To confirm the accuracy of the simulation calculation results, Pareto sets 1 and 2 have target values close to each other, and the only difference corresponding to the design factors is the atrium's plane aspect ratio. When the three relatively distant solution sets of Pareto set 1, Min EUI, and Max UDI are selected, the differences corresponding to the design factors are greater, and the calculation results are accurate.

For the Tri-directional atrium, the overall indoor daylight environment is best when the value of EUI is the smallest. At this time, the $UDI_{100\sim2000\ lux}$ is 82.9%, which indicates that the daylight comfort of the Tri-directional atrium is higher. Therefore, its main contradiction lies in solving the relationship between energy consumption and design variables. As seen by Pareto sets 1 and 3, with Min EUI and Max UDI, the Pareto preferred solution is relatable to the combination of parameters and UDI maps for the five types of solution sets shown in Table 12.

3.3.3. Bi-Directional Atrium

Similarly, Figure 10 shows that a multi-objective simulation was computed for the Bi-directional atrium, referring to the method described in Section 3.3.1. The Min EUI and Max UDI parameter values were also selected, with five target values, and the results are displayed in Tables 13 and 14.



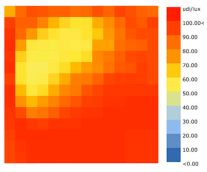
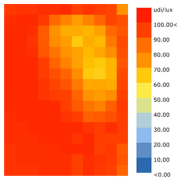
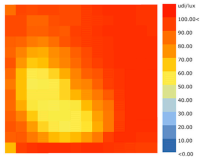
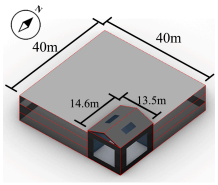
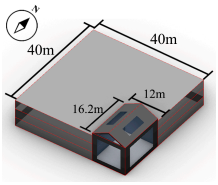
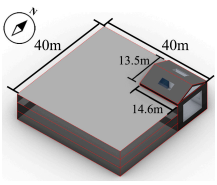
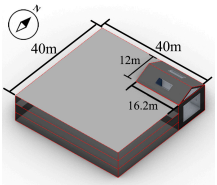
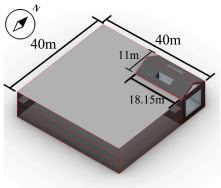
(**a**) (**b**)

Figure 10. (**a**) Pareto frontier for Bi-directional atrium; (**b**) Multi-objective sets for Bi-directional atrium.

Table 13. The objective value of each type of solution is set in the Bi-directional atrium.

Atrium Target Value.	Min EUI	Max UDI	Pareto Set 1	Pareto Set 2	Pareto Set 3
EUI (kWh/m^2)	51.4	68.8	56.9	57.8	58.9
$UDI_{100\sim2000\ lux}$ (%)	81.6	88.4	84.3	87.3	87.4

Table 14. Design parameters for various types of solutions are set in the Bi-directional atrium.

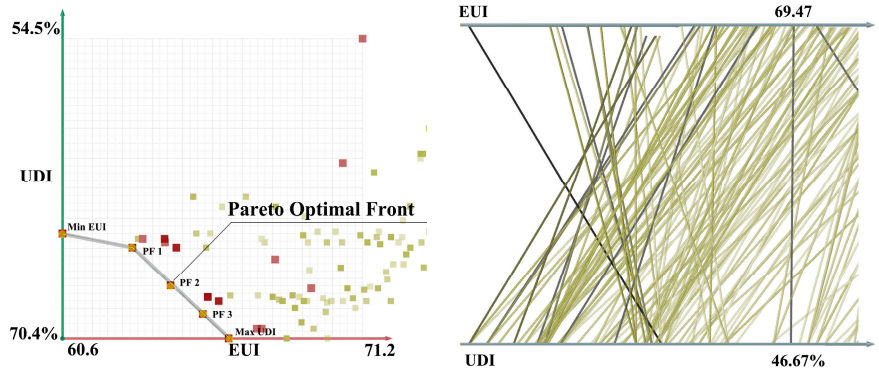
Solution Set	Min EUI	Max UDI	Pareto Set 1	Pareto Set 2	Pareto Set 3
UDI Map					
Model					

From the Pareto Frontier graph, it can be seen that the majority of solution sets are distributed near the X-axis. This indicates that the overall level of $UDI_{100\sim2000\ lux}$ is high in the Bi-directional atrium and that the overall lighting efficiency of the Bi-directional UDI is between 87.4 and 88.4%. However, the rate of increase in EUI rises, so the $UDI_{100\sim2000\ lux}$ of the solution set should be avoided to become greater than 87.4% as much as possible.

Table 14 presents the parameter combinations and UDI maps for the five types of solution sets in the Bi-directional atrium. It can be seen that the overall lighting effect of the atrium interior is better for the five solutions, except for the area facing the interior of the atrium, which has a region with lower lighting efficiency.

3.3.4. Uni-directional Atrium

A multi-objective simulation computation was conducted for the Bi-directional atrium in order to generalize the Pareto front solutions in Figure 11. The Min EUI and Max UDI parameter values were also selected, with five target values, and the results are presented in Tables 15 and 16.



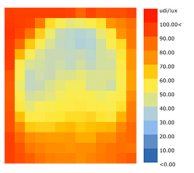
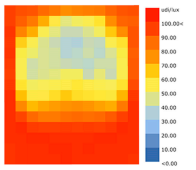
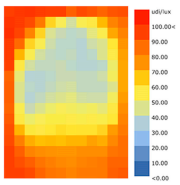
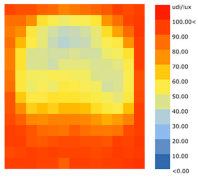
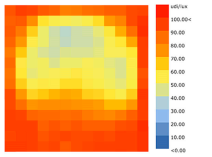
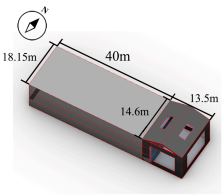
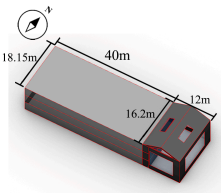
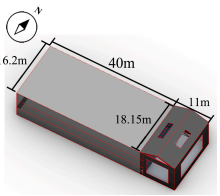
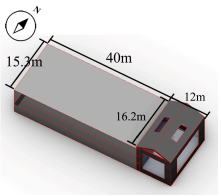
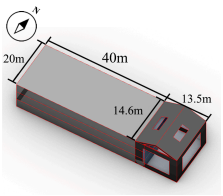
(**a**) (**b**)

Figure 11. (**a**) Pareto frontier for Uni-directional atrium; (**b**) Multi-objective sets for Uni -directional atrium.

Table 15. The objective value of each type of solution is set in the Uni-directional atrium.

Atrium Target Value	Min EUI	Max UDI	Pareto Set 1	Pareto Set 2	Pareto Set 3
EUI (kWh/m^2)	60.6	65.8	62.8	64	65
$UDI_{100\sim2000\ lux}$ (%)	60.4	70.4	61.2	64.4	68

Table 16. Design parameters for various types of solutions are set in the Uni-directional atrium.

Solution Set	Min EUI	Max UDI	Pareto Set 1	Pareto Set 2	Pareto Set 3
UDI Map					
Model					

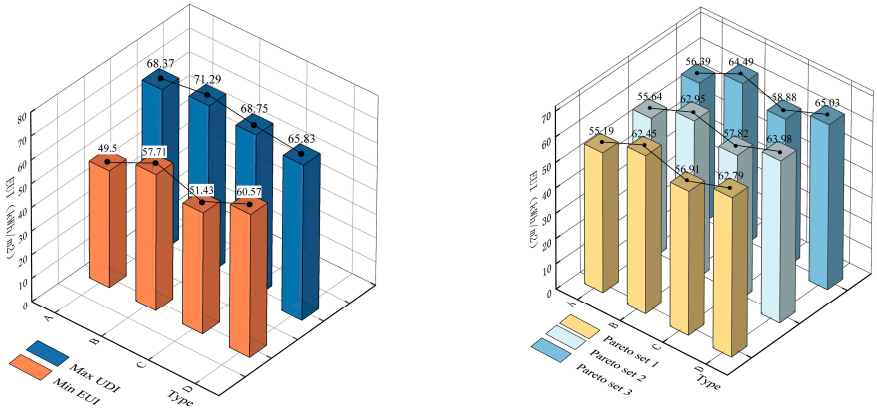
It can be observed that the distribution of the solution set is relatively average, indicating that the design factors in the Uni-directional atrium have a relatively average impact on EUI and UDI. The $UDI_{100\sim2000\ lux}$ are between 60.4% and 70.4%, with poor light environment quality caused by excessive lighting and requiring the addition of a shading system. The difference between the EUI of 60.6 and 65.8 kWh/m^2 is negligible. Thus, the optimization of the Uni-directional atrium should concentrate on the daylight environment and energy consumption.

In the meantime, three relatively distant solution sets—Pareto set 2, Min EUI, and Max UDI—are selected. The differences corresponding to the design factors increase, resulting in accurate calculation results. Tables 15 and 16 illustrate the combination of parameters from the five types of solution sets and UDI maps. These visuals demonstrate that the central portion of the Uni-directional atrium is inadequately lit due to the persistent glare that degrades the quality of the atrium's daylight comfort and must be improved with shading systems.

3.3.5. Data Analysis and Comparison

Figure 12 shows the EUI of the optimized solution set for each orientation of the atrium. The EUI of the Max UDI solution set for the Four-directional, Tri-directional, Bi-directional,

and Uni-directional atriums is 68.4, 71.3, 68.8, and 65.8 kWh/m^2, respectively, while the EUI of the Min EUI solution set are 49.5, 57.7, 51.4, and 60.6 kWh/m^2. The energy efficiency of the optimized models for each type of atrium is 8.4% to 10.3% for the Four-directional atrium, 15% to 17.6% for the Tri-directional atrium, 35% to 37.2% for the Bi-directional atriums, and 28% to 30% for the Uni-directional atriums, as compared to the data simulated by the base model.



(**a**) (**b**)

Figure 12. (**a**) Min EUI and Max UDI values in four types of atriums; (**b**) EUI values in pareto 1, 2, 3 sets for four types of atriums.

Figure 13 shows the $UDI_{100\sim2000\ lux}$ for each type of atrium's optimal solution set. The figure illustrates that the $UDI_{100\sim2000\ lux}$ values for the Max UDI solution set of Four-directional, Tri-directional, Bi-directional, and Uni-directional atriums are 89.6%, 92.9%, 88.4%, and 70.4%. In comparison, the $UDI_{100\sim2000\ lux}$ values for the Min EUI solution set are 29.6%, 82.9%, 81.6%, and 60.4%. This indicates that the Uni-directional atrium's indoor daylight comfort is inadequate and that more design optimization through shade and other measures is required.

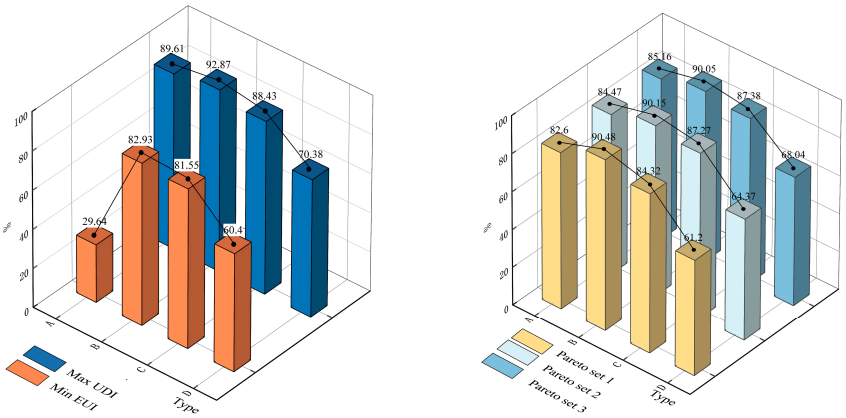


Figure 13. (**a**) Min UDI and Max UDI values in four types of atriums; (**b**) UDI values in pareto 1, 2, 3 sets for four types of atriums.

Compared to the base model, the target increments in $UDI_{100\sim2000\ lux}$ for the Pareto set of each type of atrium are as follows: 1.9% to 4.4% for Four-directional atrium; 10% to 10.4% for Tri-directional atrium; 41.7% to 44.7% for Bi-directional atrium; and 27.3% to 34.1% for Uni-directional atrium, demonstrating that the research method is effective. It can be demonstrated that the research approaches the effective daylight times of Tri-directional, Bi-directional, and Uni-directional atriums throughout the year, with the Bi-directional atrium showing the most pronounced improvement, thereby proving the method's viability. The Pareto sets 1 and 3 of each orientation atrium demonstrate that the changing trend of each

solution is identical to that of Min EUI. This validates the accuracy of the multi-objective simulation calculation findings.

3.3.6. Discussion

The research findings suggest that the energy consumption and daylight performance of atriums in college teaching buildings are influenced by various design factors. The optimal design solutions differ based on the type of atrium. Therefore, this research will present the optimization solutions for different types of atriums and elaborate on the optimization approaches. Figure 14 presents the range of values for the optimal design variables for atriums, and the following optimization design methodologies are summarized:

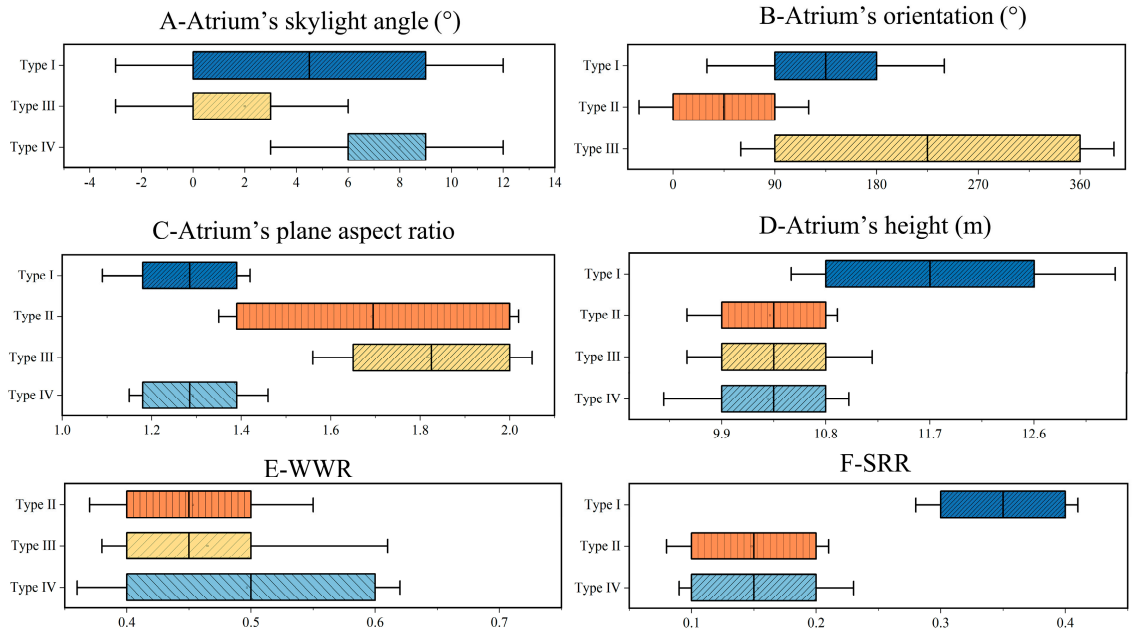


Figure 14. The range of values for design factors for each type of atrium.

The recommended ranges for fenestration factors include a WWR of 0.4 to 0.6 for Uni-directional atriums and 0.4 to 0.5 for Tri-directional and Bi-directional atriums, while the SRR is recommended to be 0.1 to 0.3 for Tri-directional and Uni-directional atriums and 0.3 to 0.4 for Four-directional atriums. The skylight angle of Four-directional atriums should be between 0° and 9°, while the skylight angles of a Bi-directional and a Uni-directional atrium should be between 0° and 3° and 6° and 9°, respectively. The orientation range of a Tri-directional atrium should be between 0° and 90°, and that of a Uni-directional atrium should be between 90° and 360°. For the height and aspect ratio of the atrium, Four-directional atriums with a square plan and a height between 10.8 m and 12.6 m are recommended as a priority. For Tri-directional and Bi-directional atriums, a rectangular shape with a height between 9.9 m and 10.8 m should be preferred. The functional characteristics of the teaching building can also impact the height and aspect ratio of the atrium. Four-directional atriums are preferred for atriums in three- to five-story teaching buildings due to their need to balance multiple objectives and provide privacy. Tri-directional atriums can improve the openness of the space while guaranteeing privacy, but they require additional modifications and optimization strategies. Bi-directional and Uni-directional atriums are recommended for atriums in two- to three-story teaching buildings, despite their relatively high energy consumption, as they provide good visual comfort and transparency. In conclusion, designers can use the recommended design parameter ranges and optimization methodologies to coordinate with the surrounding environment and enhance the building's appearance and internal space experience.

In engineering applications, designers are faced with balancing multiple objectives when considering the building form design and envelope design parameters of an atrium, with light comfort and energy consumption being the most important indicators [60]. However, since these two objectives are mutually exclusive, it is difficult for designers to effectively optimize both. While improving daylight comfort and reducing building energy consumption through high-tech devices is a common solution, the high investment cost associated with this approach limits the designer's options. Therefore, this study proposes a multi-objective optimization process for the atrium based on the passive concept. The process utilizes range analysis and ANOVA to screen design factors using the orthogonal test method, thereby avoiding the time-consuming task of acquiring upfront data [6] and filtering the design factors that need to be processed during the optimization phase. Based on this, the Octopus plug-in in Grasshopper is used for multi-objective optimization, and the Pareto optimization solution set is obtained in a short time, significantly reducing the time spent on data analysis and optimization and providing the designer with a preferred solution in a timely manner.

For users, integrating natural light into public spaces in college teaching buildings can improve their physical and mental health, enhance learning efficiency, create a better lighting environment, and increase the applicability of various types of atriums in these buildings. The findings of this study also have reference value for designing atriums in other types of buildings, such as offices, commercial buildings, hotels, and residential buildings. In future designs, renewable energy sources should be considered to reduce air pollution and carbon emissions. By reducing building energy consumption and providing a healthier and more comfortable environment, this study can contribute positively to the development of national sustainable energy and carbon reduction strategies.

4. Conclusions

In order to effectively screen design elements and improve the performance of atriums, this study has utilized orthogonal tests and multi-objective optimization methods to analyze the feasibility of building design and construct a corresponding research process. Firstly, four types of atriums in cold regions were researched, and the base model was established through typological abstract evolution. Then, the light comfort and energy consumption of the atrium were simulated using Ladybug Tools in Grasshopper, and the resulting data were imported into the orthogonal test table. By using range analysis and ANOVA, the degree of influence of various atrium design factors on energy usage was determined, and the less significant design factors were eliminated. Based on this, Octopus was utilized for multi-objective optimization. The findings show that an early atrium design based on passive concepts can generate excellent performance solutions to meet the diverse and open functions of teaching buildings in the new era. This provides a useful guideline for the design and optimization of teaching building atriums. The following are the study's findings:

1. Fenestration has the greatest impact on atrium energy consumption, followed by building form and an opaque envelope. Among the building form designs, atrium height has the greatest influence on energy consumption.
2. Relative to the base model, the energy-saving rates of the four optimized atrium solutions are 10.3%, 17.6%, 37.2%, and 30.5%, with the Bi-directional atrium having the greatest energy-saving potential and the Uni-directional atrium having the foremost.
3. Relative to the base model, the percentage improvement in light comfort for the four optimized atrium solutions is 4.4%, 10.4%, 44.7%, and 34.1%, respectively. The optimized design improves the daylight comfort of the Bi-directional and Uni-directional atriums, with $UDI_{100\sim2000\,lux}$ above 80%.

However, this study has some limitations. Firstly, this study only focuses on early-stage design factors of the atrium, which may not provide a comprehensive solution. Future research should consider more detailed design factors to optimize the atrium design. Secondly, this study exclusively focused on examining the impact of atrium

design factors on light comfort and energy consumption without taking into account their influence on other indoor environmental factors, such as thermal comfort, acoustic conditions, and indoor air quality. Lastly, the study only analyzes atrium design methods for buildings in cold regions, and further research is needed to examine atrium design methods in other climate zones. Overall, future research endeavors should aim to integrate the effects of design factors on atrium thermal comfort and indoor air quality. This could involve validating simulation results through empirical measurements to address intricate challenges in real-world projects, ultimately establishing a more robust scientific basis for atrium design methodologies.

Author Contributions: Methodology, H.Z.; software, Z.C. and S.Z.; validation, H.Z.; formal analysis, Z.C.; investigation, H.Z.; data curation, R.W.; writing—original draft preparation, Z.C.; writing—review and editing, Z.C.; visualization, R.W.; supervision, Y.C.; project administration, Y.C. All authors have read and agreed to the published version of the manuscript.

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References

1. Franco, M.; Pawar, P.; Wu, X. Green building policies in cities: A comparative assessment and analysis. *Energy Build.* **2021**, *231*, 110561. [CrossRef]
2. Huang, Y.; Yu, Q.; Wang, R. Driving factors and decoupling effect of carbon footprint pressure in China: Based on net primary production. *Technol. Forecast. Soc. Chang.* **2021**, *167*, 120722. [CrossRef]
3. Hu, M.; Zhang, K.; Nguyen, Q.; Tasdizen, T. The effects of passive design on indoor thermal comfort and energy savings for residential buildings in hot climates: A systematic review. *Urban Clim.* **2023**, *49*, 101466. [CrossRef]
4. Rodriguez-Ubinas, E.; Montero, C.; Montero, M. Passive design strategies and performance of net energy plus houses. *Energy Build.* **2014**, *83*, 10–22. [CrossRef]
5. Stevanović, S. Optimization of passive solar design strategies: A review. *Renew. Sustain. Energy Rev.* **2013**, *25*, 177–196. [CrossRef]
6. Gong, X.; Akashi, Y.; Sumiyoshi, D. Optimization of passive design measures for residential buildings in different Chinese areas. *Build. Environ.* **2012**, *58*, 46–57. [CrossRef]
7. Konis, K.; Gamas, A.; Kensek, K. Passive performance and building form: An optimization framework for early-stage design support. *Sol. Energy* **2016**, *125*, 161–179. [CrossRef]
8. Whitson, B.; Houska, C. *Skylight Handbook, Design Guidelines*; American Architectural Manufacturers Association: Des Plaines, IL, USA, 1987.
9. Thumann, A.; Young, W. *Design for Energy Conservation with Skylights*; Architectural Aluminum Manufacturers Association: Chicago, IL, USA, 1981.
10. Aldawoud, A. The influence of the atrium geometry on the building energy performance. *Energy Build.* **2013**, *57*, 1–5. [CrossRef]
11. Tabesh, T.; Sertyesilisik, B. An investigation into energy performance with the integrated usage of a courtyard and atrium. *Buildings* **2016**, *6*, 21. [CrossRef]
12. Ghasemi, M.; Noroozi, M.; Kazemzadeh, M.; Roshan, M. The influence of well geometry on the daylight performance of atrium adjoining spaces: A parametric study. *J. Build. Eng.* **2015**, *3*, 39–47. [CrossRef]
13. Rastegari, M.; Pournaseri, S.; Sanaieian, H. Daylight optimization through architectural aspects in an office building atrium in Tehran. *J. Build. Eng.* **2021**, *33*, 101718. [CrossRef]
14. Li, Z.; Yu, D.; Xu, W.; Zhang, M.; Geng, W.; Li, N. Research on the reconstruction design of the closed atrium of the No. 1 office building of Wuhan Kaidi. *Buildings* **2022**, *12*, 1674. [CrossRef]
15. Dong, L.; He, Y.; Qi, Q.; Wang, W. Optimization of daylight in atrium in underground commercial spaces: A case study in Chongqing, China. *Energy Build.* **2022**, *256*, 111739. [CrossRef]
16. Xue, Y.; Liu, W. A study on parametric design method for optimization of daylight in commercial building's atrium in cold regions. *Sustainability* **2022**, *14*, 7667. [CrossRef]
17. Berardi, U.; Wang, T. Daylighting in an atrium-type high performance house. *Build. Environ.* **2014**, *76*, 92–104. [CrossRef]
18. Danielski, I.; Nair, G.; Joelsson, A.; Fröling, M. Heated atrium in multi-storey apartment buildings, a design with potential to enhance energy efficiency and to facilitate social interactions. *Build. Environ.* **2016**, *106*, 352–364. [CrossRef]
19. Wang, Y.; Yang, W.; Wang, Q. Multi-objective parametric optimization of the composite external shading for the classroom based on lighting, energy consumption, and visual comfort. *Energy Build.* **2022**, *275*, 112441. [CrossRef]

20. Liu, Q.; Ren, J. Research on the building energy efficiency design strategy of Chinese universities based on green performance analysis. *Energy Build.* **2020**, *224*, 110242. [CrossRef]
21. Baker, N.; Steemers, K. *Energy and Environment in Architecture: A Technical Design Guide*; E&FN SPON: London, UK; E&FN SPON: New York, NY, USA, 2003.
22. Wang, L.; Huang, Q.; Zhang, Q.; Xu, H.; Yuen, R.K. Role of atrium geometry in building energy consumption: The case of a fully Air-conditioned enclosed atrium in cold climates, China. *Energy Build.* **2017**, *151*, 228–241. [CrossRef]
23. Cho, J.; Yoo, C.; Kim, Y. Viability of exterior shading devices for high-rise residential buildings: Case study for cooling energy saving and economic feasibility analysis. *Energy Build.* **2014**, *82*, 771–785. [CrossRef]
24. Cheng, C.; Chen, C.; Chou, C.; Chan, C. A mini-scale modeling approach to natural daylight utilization in building design. *Build. Environ.* **2007**, *42*, 372–384. [CrossRef]
25. Asfour, O. A comparison between the daylighting and energy performance of courtyard and atrium buildings considering the hot climate of Saudi Arabia. *J. Build. Eng.* **2020**, *30*, 101299. [CrossRef]
26. Du, J.; Sharples, S. The assessment of vertical daylight factors across the walls of atrium buildings, Part 1: Square atria. *Light. Res. Technol.* **2012**, *44*, 109–123. [CrossRef]
27. Vujošević, M.; Krstić-Furundžić, A. The influence of atrium on energy performance of hotel building. *Energy Build.* **2017**, *156*, 140–150. [CrossRef]
28. Li, J.; Ban, Q.; Chen, X.; Yao, J. Glazing sizing in large atrium buildings: A perspective of balancing daylight quantity and visual Comfort. *Energies* **2019**, *12*, 701. [CrossRef]
29. Lu, Y.; Xiang, Y.; Chen, G.; Wu, Y.; Sun, C.; Liu, J. Summer dynamic thermal environment for isolated atrium in the severe cold region: On-site measurement and numerical simulation. *Appl. Therm. Eng.* **2019**, *160*, 114108. [CrossRef]
30. Wu, X.; Oldfield, P.; Heath, T. Spatial openness and student activities in an atrium: A parametric evaluation of a social informal learning environment. *Build. Environ.* **2020**, *182*, 107141. [CrossRef]
31. Fan, Z.; Zehui, Y.; Liu, Y. Daylight performance assessment of atrium skylight with integrated semi-transparent photovoltaic for different climate zones in China. *Build. Environ.* **2020**, *190*, 107299. [CrossRef]
32. Wu, P.; Zhou, J.; Li, N. Influences of atrium geometry on the lighting and thermal environments in summer: CFD simulation based on-site measurements for validation. *Build. Environ.* **2021**, *197*, 107853. [CrossRef]
33. Li, J.; Zhu, N. The impact evaluation of the passive adjustment performance of intermediate space in buildings: A case study of the atrium space in large public buildings. *Archit. J.* **2016**, *9*, 108–113.
34. Li, J.; Lu, S.; Wang, Q. Graphical visualisation assist analysis of indoor environmental performance: Impact of atrium spaces on public buildings in cold clim ates. *Indoor Built Environ.* **2016**, *27*, 331–347. [CrossRef]
35. Hou, H.; Zhang, Q.; Huang, Q. Constructing the design strategy chart of low-Energy atriums in cold regions. *Archit. J.* **2016**, *5*, 72–76.
36. Sher, F.; Kawai, A.; Güleç, F.; Sadiq, H. Sustainable energy saving alternatives in small buildings. *Sustain. Energy Technol. Assess.* **2019**, *32*, 92–99. [CrossRef]
37. Shafiei Fini, A.; Moosavi, A. Effects of "wall angularity of atrium" on "buildings natural ventilation and thermal performance" and CFD model. *Energy Build.* **2016**, *121*, 265–283. [CrossRef]
38. Hussain, S.; Oosthuizen, P. Numerical study of buoyancy-driven natural ventilation in a simple three-storey atrium building. *Int. J. Sustain. Built Environ.* **2012**, *1*, 141–157. [CrossRef]
39. Nguyen, A.-T.; Reiter, S.; Rigo, P. A review on simulation-based optimization methods applied to building performance analysis. *Appl. Energy* **2014**, *113*, 1043–1058. [CrossRef]
40. Roudsari, M.; Pak, M. Ladybug: A parametric environmental plugin for grasshopper to help designers create an environmentally-conscious design. In Proceedings of the 13th Conference of International Building Performance Simulation Association, Chambery, France, 26–28 August 2013.
41. Attia, S.; Hamdy, M.; O'Brien, W.; Carlucci, S. Computational optimization for zero energy buildings design: Interview results with twenty-eight international experts. In Proceedings of the 13th Conference of International Building Performance Simulation Association, Chambery, France, 26–28 August 2013.
42. Hung, W.; Chow, W. A review on architectural aspects of atrium buildings. *Archit. Sci. Rev.* **2001**, *44*, 285–295. [CrossRef]
43. Sharples, S.; Lash, D. Daylight in atrium buildings: A critical review. *Archit. Sci. Rev.* **2011**, *50*, 301–312. [CrossRef]
44. He, B.-J. Towards the next generation of green building for urban heat island mitigation: Zero UHI impact building. *Sustain. Cities Soc.* **2019**, *50*, 101647. [CrossRef]
45. Xi, C.; Ding, J.; Ren, C.; Wang, J.; Feng, Z.; Cao, S.-J. Green glass space based design for the driven of sustainable cities: A case study. *Sustain. Cities Soc.* **2022**, *80*, 103809. [CrossRef]
46. *GB 50189-2015*; Design Standard for Energy Efficiency of Public Buildings. Ministry of Housing and Urban-Rural Development: Beijing, China, 2015.
47. Tian, Z.; Zhang, X.; Jin, X.; Zhou, X.; Si, B.; Shi, X. Towards adoption of building energy simulation and optimization for passive building design: A survey and a review. *Energy Build.* **2018**, *158*, 1306–1316. [CrossRef]
48. *GB 50736-2012*; Design Code for Heating Ventilation and Air Conditioning of Civil Buildings. Ministry of Housing and Urban-Rural Development: Beijing, China, 2012.

49. *GB 50033-2013*; Standard for Daylighting Design of Buildings. Ministry of Housing and Urban-Rural Development: Beijing, China, 2013.
50. *ASHRAE STANDARD 62.1*; Ventilation for Acceptable Indoor Air Quality. ASHRAE: Atlanta, GA, USA, 2022.
51. Illuminating Engineering Society (IES). ANSI/IES LS-1-22. Available online: https://www.ies.org/definitions/spatial-daylight-autonomy-sda/ (accessed on 7 September 2023).
52. Cantin, F.; Dubois, C. Daylighting metrics based on illuminance, distribution, glare and directivity. *Light. Res. Technol.* **2011**, *43*, 291–307. [CrossRef]
53. Nabil, A.; Mardaljevic, J. Useful daylight illuminances: A replacement for daylight factors. *Energy Build.* **2006**, *38*, 905–913. [CrossRef]
54. Nabil, A.; Mardaljevic, J. Useful daylight illuminance: A new paradigm for assessing daylight in buildings. *Light. Res. Technol.* **2005**, *37*, 41–57. [CrossRef]
55. Carlucci, S.; Causone, F.; De Rosa, F.; Pagliano, L. A review of indices for assessing visual comfort with a view to their use in optimization processes to support building integrated design. *Renew. Sustain. Energy Rev.* **2015**, *47*, 1016–1033. [CrossRef]
56. Lindelöf, D.; Morel, N. A field investigation of the intermediate light switching by users. *Energy Build.* **2006**, *38*, 790–801. [CrossRef]
57. Reinhart, C.F.; Voss, K. Monitoring manual control of electric lighting and blinds. *Light. Res. Technol.* **2003**, *35*, 243–258. [CrossRef]
58. Tahsildoost, M.; Zomorodian, Z. Energy retrofit techniques: An experimental study of two typical school buildings in Tehran. *Energy Build.* **2015**, *104*, 65–72. [CrossRef]
59. Seberry, J. *Orthogonal Designs*; Springer: Berlin, Germany, 2011.
60. Uribe, D.; Bustamante, W.; Vera, S. Potential of perforated exterior louvers to improve the comfort and energy performance of an office space in different climates. *Build. Simul* **2018**, *11*, 695–708. [CrossRef]

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