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Research on Energy-saving Design for University Library Spaces in Cold Regions

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ABSTRACT: With the popularization of open-shelf reading in university library, the change of use mode leads to the change of space mode, and gradually develops from corridor mode to large-scale and deep composite centralized space organization mode. However, the large and deep open reading space and atrium space in university libraries increasingly rely on artificial lighting, mechanical ventilation and mechanical temperature regulation to meet the comfort needs of space thermal environment. Moreover, the improper control of passive design strategy in the early stage further leads to the reduction of indoor thermal environment comfort and the increase of building energy consumption. In the early stage of architectural design, through reasonable passive space layout design, the use of air conditioning equipment can be greatly reduced, energy consumption can be reduced, and the goal of green development can be achieved. Through extensive collection and analysis of 23 university libraries built in cold climate region, by making a statistical study on the building type, building area, number of floors, building scale and building plane aspect ratio, summarizing and extracts the prototype. Referring to the typical cases in cold climate area, two core groups that reading spatial variable group and atrium spatial variable group are proposed by controlling a single variable, in which each group has four plane layout modes. The dynamic energy consumption simulation software DesignBuilder is used to simulate the annual cooling, heating and lighting load of each group in cold climate region, and the results are converted into energy consumption values for analysis. The final results show that among the four combination modes of reading spatial variable group, the overall energy consumption of compound type is the smallest, and the energy-saving rate is the highest, up to 3.71% . The overall energy consumption of parallel type and surround type is little difference, and the overall energy consumption of surround type is the highest. The energy-saving rate of the four groups of reading modes is as follows: compound type> decentralized type> parallel type> surround type. The total energy consumption of the atrium partial staggered floor group is lower than that of the non staggered floor group. Among the four combination modes of the atrium spatial variable group, the overall energy consumption of the organization form of the atrium partial staggered floor to the south is the smallest, the energy-saving rate is the highest, reaching 5.84% , and the energy-saving rate of the atrium partial staggered floor to the north is the lowest. Therefore, in the preliminary scheme design stage, low-performance spaces such as traffic auxiliary space can be placed at the building boundary to form a buffer zone similar to the transition space, so as to alleviate the negative impact of the external adverse climate environment on the internal space. At the same time, it can be considered to carry out partial staggered floor design of the atrium, and give priority to arranging the atrium on the south side, which is not only conducive to reducing the overall energy consumption of the building and achieving the

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energy-saving goal, but also enhance the diversification of vertical sections and promote the interest of the internal space of modern university libraries.

KEY WORDS: university library; functional organization; energy consumption simulation; energy saving design

1 Background and problem

In recent years, with the popularization of open shelves, libraries have been increasingly focused on "people-oriented" service design in terms of functional goals. Buildings have gradually shifted from the corridor layout pattern driven by functional zoning to a modular spatial design. That is, while preserving the functional zoning of "collecting, borrowing, reading and managing," small segmented spaces are merged into spacious and illuminated areas, and linear circulation spaces are consolidated into block spaces [1]. These spaces also serve cultural services, open education, and leisure and entertainment functions [2]. Changes in way of use have led to changes in spatial patterns. Representative examples, such as university libraries, have evolved towards composite centralized spatial organizations of large-scale, high-volume, and great-depth. Horizontal and vertical flow openness has become their main characteristic, greatly enriching the diversity of functional spaces.

However, open reading spaces with significant depth increasingly rely on artificial lighting, mechanical ventilation, and mechanical temperature regulation to meet the requirements for thermal comfort of the space. Improper control of passive design strategies during the initial stages further reduces indoor thermal comfort and increases building energy consumption [3,4]. For instance, in libraries with inadequate functional layouts, artificial lighting is necessary even during daytime, resulting in significantly increased lighting energy consumption. Simultaneously, improper spatial organization leads to excessive light intensity in certain areas, poor thermal comfort, and high air conditioning loads. Through investigations, it has been observed that even with air conditioning, readers in some libraries' reading areas still feel hot and need to use umbrellas while studying. Additionally, inefficient design patterns in core functional reading areas of certain libraries result in low utilization rates and poor efficiency. These problems not only result in high operational, management, and maintenance costs, but also significantly increase energy resource waste, contradicting the concept of sustainable development for libraries.

During the initial design phase of a building, providing effective strategies for passive energy-saving measures can facilitate architects in implementing rational energy-saving designs. By utilizing the climate analysis program, Weather Tool, a sub-software of the ecological building design software Ecotect, and combining it with typical meteorological year data (CSWD), an analysis of the climatic conditions in cold climate zones, represented by Beijing, was conducted. As shown in Figure 1 and Figure 2, Optimum Orientation and Psychrometric Chart, the optimal orientation for the layout was found to be a southeast deviation of 17.5°. Employing passive techniques such as natural ventilation and passive solar heating through spatial organization significantly improved the range of human comfort. Therefore, a well-designed passive spatial layout can greatly reduce the use of air conditioning equipment and decrease energy consumption. In general, the core problem that contemporary university libraries face is how to achieve a balance between meeting innovative demands and minimizing overall energy consumption while ensuring optimal comfort through functional spatial organization design. This has practical significance for the sustainable development of university libraries.

Thus, by collecting existing completed cases of university libraries in cold climate zones, extracting model prototypes, selecting Beijing as a representative city for cold climate regions, and utilizing the simulation software of energy comsumption DesignBuilder, this study explores the impact of functional spatial design on energy consumption in library buildings and proposes optimization recommendations for the internal spatial organization suitable for cold climate regions based on energy-saving effects.

2 Current situation of university library architectural design and selection of the model prototype

2.1 Extraction of university library model prototypes

In building energy efficiency evaluation, it is essential to first identify the energy efficiency contribution of the building itself, as the external form has different impacts on the energy consumption of libraries [5-7]. Therefore, an extensive collection of 23 completed cases of university libraries in cold climate zones was analyzed to conduct statistical research of the architectural form, floor area, number of floors, building scale, and aspect ratio of the building plan. For selected representative cases, the arithmetic average values were used to summarize and extract the simulation prototype, resulting in a prototype with a floor area of 34,520 m^2, five floors, with an interior atrium which has the aspect ratio of 1 ∶ 1, and the building plan's aspect ratio is 1 ∶ 1.

2.2 Selection and design of functional spaces within the library

The energy consumption levels vary based on the different functionalities of spaces within a building. Therefore, transforming functional classification into performance-rating classification is an important development in the theory of functional zoning for public buildings. Its significance lies in understanding and grasping the inherent connection between building functions, performance, and energy consumption [8]. By establishing a rational layout of functional spaces, climate adaptability in architectural spatial design can be achieved, laying, as a precondition, the foundation for green energy-efficient design by reducing energy consumption and emissions. Based on the degree of strictness of the requirements for climatic performance factors and indicators in its specification, the spaces can be categorized as low-performance spaces, regular-performance spaces, and high-performance spaces [9].

In library buildings, spaces for reading and study, as well as office spaces, have higher requirements for thermal comfort according to the specification, thus they are defined as high-performance spaces. Regular-performance spaces consist of secondary functional spaces, such as exhibition areas and report rooms. The remaining functional spaces, such as traffic and other auxiliary areas, which have lower occupancy rates and personnel density, are defined as low-performance spaces. The areas and proportions of each space are shown in Table 2 and reasonably selected based on the "Library Building Design Specification JGJ38-2015" [10].

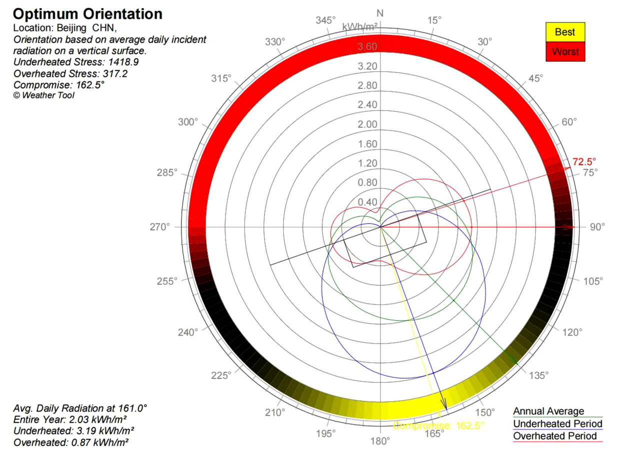


Figure 1 Optimum orientation chart for cold climate zone (Beijing)

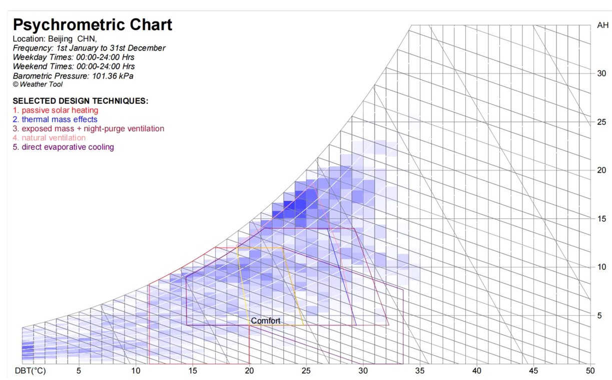


Figure 2 Psychrometric chart for cold climate zone (Beijing)

3 Establishment of spatial organization models for university libraries

3.1 Selection and setting of spatial organization variables

As the main functional space in libraries, reading spaces have higher standards for lighting and thermal environment, and different organizational patterns and layout methods also significantly impact the overall energy consumption of the buildings [11]. Simultaneously, as high-performance spaces, the form design of tall atria are closely related to the energy consumption as well [12]. Therefore, two core groups of variables are proposed: the reading space variable group and the atrium space variable group.

(1) Reading Space Variable Group: The relative position of reading spaces and traffic spaces in the plan is taken as the variable. That is, while excluding the variables and ensuring the area, position, and form of other

functional spaces remain unchanged, the layout of the reading space is indirectly altered by changing the position of traffic and auxiliary spaces in the plan. This explores the variations in energy consumption under different reading modes.

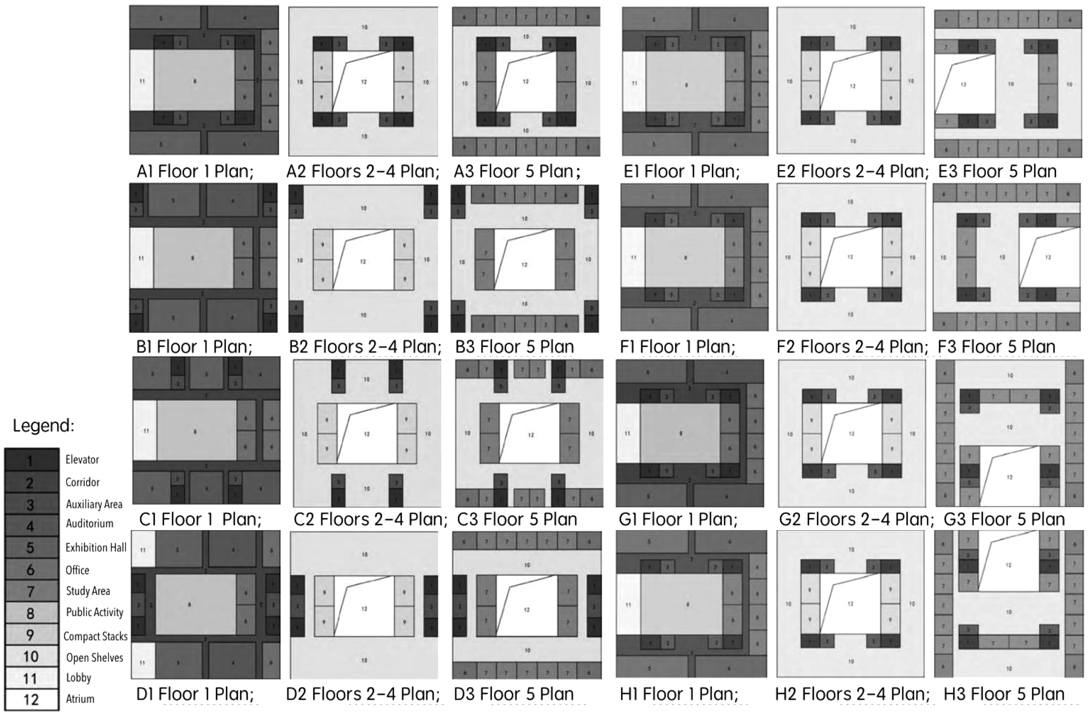


Figure 3 Floor plans of different simulation groups (Groups A-D: variation of reading spaces; groups E-H: variation of atrium spaces)

(2) Atrium Space Variable Group: The relative position of the atrium space in the plan is taken as the variable. By changing the direction of partial staggered floors of the atrium space and the orientation arrangement of study spaces, the influence of tall atria on the energy consumption of university libraries is studied.

3.2 Setting of simulation groups and model construction

Based on the two aforementioned variables, and in reference to typical spatial layouts in cold regions, along with the requirements of library functional circulation and energy-efficient design research from design codes [13], eight representative spatial organization patterns are formed. Groups A-D represent the reading space variable group, while groups E-H represent the atrium space variable group. The floor plans of each group are shown in Figure 3.

Group A adopts a simplified floor layout pattern based on the typical case of the Library of Beijing University of Civil Engineering and Architecture in a cold climate region. The atrium serves as the core space of the library, with vertical traffic auxiliary spaces centrally located in the four corners of the atrium. The first floor comprises lecture halls, exhibition spaces, and office areas, while the second to fourth floors consist of horizontally surrounding open reading spaces and book storage areas. The fifth floor is dedicated to study spaces.

Group B adopts a simplified floor layout pattern based on the typical case of the Library of Changqing Campus, Shandong Normal University, in a cold climate region. In this layout, less energy-consuming traffic auxiliary spaces are placed in the corners of the building's overall form, turning the reading spaces into a horizontally composite arrangement.

Group C refers to the simplified floor plan layout pattern of the Beijing Central University of Finance and Economics Library, which is a typical case in cold climate areas. In this pattern, energy-efficient transportation auxiliary spaces are located on the north and south sides of the building's floor plan, while the concentrated reading spaces are divided into multiple smaller spaces, forming a horizontally dispersed layout.

Table 1 Statistics of university library cases

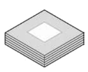
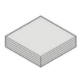
Architectural sketch	Case Name	Floor Area	Number of Floors	Building Scale(m)	Aspect Ratio	Presence of Atrium
	Tsinghua University Law School Library	20,000 m^2	Above Ground:8+ Below Ground: 2	51 × 51	1∶1	Yes (87%)
	Beijing Institute of Architectural Engineering Library	34,169 m^2	Above ground:7+ Below ground: 1	61 × 61	1∶1	
	Nankai University Library, Tianjin	36,400 m^2	Above ground:5+ Below ground: 1	82 × 74	1∶1	
	China Agricultural University Library	48,725 m^2	Above ground:7+ Below ground: 1	38 × 38	1∶1	
	Northwest Textile College Library	23,450 m^2	Above ground:5+ Below ground: 1	68 × 57	1∶1	
	Shandong University of Science and Technology Library	17,052 m^2	Above ground:6+ Below ground: 1	58 × 42	3∶2	
	Tianjin University Beiyangyuan Campus Library	20,880 m^2	5	67 × 65	1∶1	
	Northwest University Library	30,960 m^2	6	82 × 75	1∶1	
	Central University of Finance and Economics Library, Beijing	30,400 m^2	5	88 × 72	1∶1	
	Anhui University of Science and Technology Library	28,220 m^2	4	88 × 80	1∶1	
	Taiyuan NormalUniversity Library	29,840 m^2	5	82 × 80	1∶1	
	Shaanxi Institute of Mining Library	13,800 m^2	6	53 × 50	1∶1	
	Gansu Agricultural University Library	6,906 m^2	5	47 × 47	1∶1	
	Shaanxi Normal University Chang'an Campus Library	10,450 m^2	5	44 × 44	1∶1	
	Shandong Normal University Changqing Campus Library	34,820 m^2	6	78 × 75	1∶1	
	Shandong University of Science and Technology Library	25,578 m^2	7	64 × 58	1∶1	
	Yantai University Library	14,300 m^2	4	60 × 45	3∶2	
	Shangqiu Normal University Library	6,017 m^2	5	65 × 47	3∶2	
	Lanzhou University Library	20,890 m^2	6	62 × 58	1∶1	
	Taiyuan Polytechnic Institute Library	24,480 m^2	5	72 × 68	1∶1	No (13%)
	Henan Xinxiang Medical University Library	9,080 m^2	4	55 × 41	1∶1	
	Hebei University of Technology Library	5,796 m^2	3	46 × 42	1∶1	
	Qinghai Normal University Library	9,504 m^2	Above ground:4+ Below Ground: 1	44 × 36	1∶1	

Table 2 Classification of performance spaces

Performance space types	Functional space names	Area(m^2)	Percentage of functional space(%)	Percentage of performance space(%)
High-performance spaces	Reading spaces	21,540	62	73
	Study spaces	3,040	8	
	Office spaces	885	3	
Regular-performance spaces	Report and exhibition spaces	885	3	17
	Public activity spaces	2,340	7	
	Book storage spaces	2,480	7	
Low-performance spaces	Traffic spaces	2,010	6	10
	Auxiliary spaces	1,340	4	

Group D refers to the simplified floor plan layout pattern of the Tianjin Nankai University Library, which is another typical case in cold climate areas. In this pattern, energy-efficient transportation auxiliary spaces are located on the east and west sides of the building's floor plan, while the concentrated reading spaces are divided into two reading areas, north and south, forming a horizontally parallel pattern. To ensure the accuracy of the results of this simulation which controlls a single variable, the layout forms and orientations of other functional spaces on each floor in Groups B, C, and D are the same as Group A.

Groups E, F, G, and H, based on Group A and with minimal changes to the positions, areas, and layouts of other functional spaces, modify a single variable by staggering the position of the full-height atrium on the fifth floor to the west, east, south, and north sides respectively. This means that the large and energy-consuming atrium space of the building is divided into two connected vertical composite atrium spaces in the section. Analyzing the section, the core consists of a vertically full-height staggered atrium, with vertical transportation spaces in the middle, and a combination pattern of north-south or east-west study spaces on the outer side of the top floor. The Design Builder model photos are shown in Figure 4.

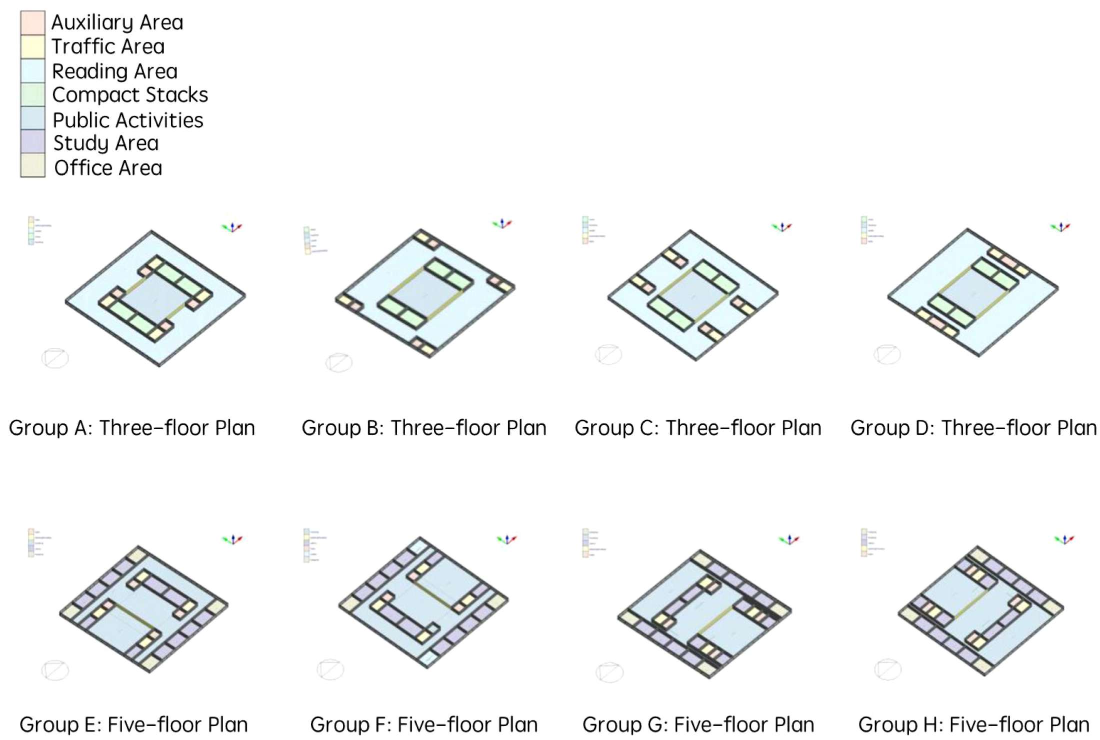


Figure 4 Design builder model floor plans

To facilitate the comparative analysis of simulation results in the following text, the attributes, patterns, and methods of controlling variables for each group are summarized in Table 3.

3.3 Selection of simulation software and setting of simulation parameters

The simulation of library buildings relies on the dynamic energy-consumption simulation software Design Builder, with Energy-Plus as the calculation engine. This software provides thermal properties of climates, buildings, components, as well as operational schedules and the HVAC equipment. The climate data is in CSWD format and was set according to the "Specialized Meteorological Dataset for Analysis of Thermal Environment in Chinese Buildings" compiled by the Meteorological Information Center of the China Meteorological Administration, under the editorial supervision of the Department of Building Science and Technology at Tsinghua University. Meteorological parameters were selected from data specific to Beijing, representing a typical city in cold regions, in order to provide a basis for studying the relationship between different spatial organization patterns and energy consumption. The simulation outputs include cooling load, heating load, and lighting energy consumption, which are evaluated based on the total energy consumption and energy-saving efficiency values after being converted to COP values.

The performance parameters of each functional space were set based on the parameters specified in the "Green Performance Calculation Standard for Civil Buildings JGJ/T449-2018" [14] and the "Design Specification for Library Buildings JGJ38-2015" [10]. Parameters that are not specified in the standards and specifications were set according to the default values in the software template. The specific parameters are shown in Table 4.

The building envelope structure plays a crucial role in resisting external adverse environmental factors, and different selections and configurations have a significant impact on building energy consumption [15]. The parameters of the envelope structure in the model are set according to the thermal performance limits for public building envelopes in cold climate regions specified in the "Energy-saving Design Standard for Public Buildings" [16]. The thermal parameters designated in the standard are used as default parameters in the simulation, as shown in Table 5.

Table 3 Simulation group settings

Group ID	Group name	Layout combination patterns	Variable1		Variable 2	
			Reading space Layout	Traffic space layout	Atrium space layout	Study space layout
A	Reading space variable group	Surrounding reading + traffic center	Surrounding style	Central style	Core style	Side style (North-south)
B		Composite reading + corner traffic	Composite style	Corner style	Core style	Side style (North-south)
C		Dispersed reading + North-south traffic	Dispersed style	Side style (North-south)	Core style	Side style (North-south)
D		Parallel reading + East-west traffic	Parallel style	Side style (East-west)	Core style	Side style (North-south)
E	Atrium space variable group	West side staggered + North-south study	Surrounding style	Central style	Composite style (East)	Side style (North-south)
F		East side staggered + North-south study	Surrounding style	Central style	Composite style (North)	Side style (North-south)
G		South side staggered + East-west study	Surrounding style	Central style	Composite style (south)	Side style (East-west)
H		North side staggered + East-west study	Surrounding style	Central style	Composite style (West)	Side style (East-fest)

4 Comparison and analysis of simulation results

The Design Builder software is used to simulate the annual heating and cooling loads and lighting loads, and the output summary provides the results of heat and cool supply (in terms of kWh). These values are then converted into energy consumption values for analysis according to the standard of the cooling-heating source system's coefficient of performance (COP).

4.1 Energy consumption analysis of reading space groups

4.1.1 Annual cooling and heating energy consumption per unit area

The simulation shows that Group A has the highest values for annual cooling energy consumption per unit area and annual heating energy consumption per unit area, which are 15.76 kWh/m^2/yr and 17.84 kWh/m^2/yr, respectively. At the same time, as seen in Figure 5, groups B, C, and D, which have low-performance traffic areas located at the climate boundary, exhibit reduced cooling and heating energy consumption per unit area in all climate zones compared to Group A, which has high-performance reading spaces surrounding the climate boundary. This indicates that placing low-performance spaces at the climate boundary can act as a buffer against adverse external climatic factors.

Group B places the traffic spaces at the four corners, and the reading spaces are arranged in a horizontally centralized manner, resulting in the most noticeable energy-saving effect. It has the lowest values for annual cooling energy consumption per unit area and annual heating energy consumption per unit area, which are 14.70 kWh/m^2/yr and 14.77 kWh/m^2/yr, respectively. Additionally, Group C also exhibits lower values for annual cooling and heating energy consumption per unit area, which are 15.12 kWh/

m^2/yr and 15.84 kWh/m^2/yr, respectively. This indicates that when the form of the reading spaces is horizontally dispersed-style, that is to say, dividing a single open high-performance reading area into multiple small reading spaces, it can also contribute to reducing energy consumption to some extent. The ranking of annual cooling and heating energy consumption per unit area is as follows: Group A > Group D > Group C > Group B.

Table 4 Functional space parameter settings

Functional space name	Lighting power density (W/m^2)	Equipment power density (W/m^2)	Personnel density (m^2/ person)	Personnel heat dissipation (W/ person)	Fresh air volume [m^3/(h·person)]	Room summer set temperature (℃)	Room winter set temperature (℃)	Room illuminance (lx)	Reference plan and height (m)
Compact stacks	7	5	/	/	10	28	14	50	0.25m (vertical plane)
Open shelves	9	5	1.9	108	30	26	20	300	0.75m (horizontal plane)
Exhibition hall	9	5	2.5	108	30	26	18	300	0.75m (horizontal plane)
Lecture hall	9	5	2.5	108	30	26	18	300	0.75m (horizontal plane)
Administrative office	9	5	6	134	30	26	20	300	0.75m (horizontal plane)
Corridor	5	5	/	134	20	26	16	75	ground
Elevator	5	5	/	134	20	28	16	75	ground
Restroom	6	5	20	134	20	28	16	75	ground
Study and discussion	9	5	6	108	30	26	20	300	0.75m (horizontal plane)
Lobby	8	5	1.5	134	20	26	16	150	ground
Public activities	8	5	10	181	30	26	20	200	0.75m (horizontal plane)

Table 5 Parameters for envelope structure

Envelope structure	Construction layers (from outside to inside)	Thickness	Heat transfer coefficient ($W/m^2 \cdot k$)
External wall	Cement mortar	20 mm	0.27
	Extruded polystyrene foam board	60 mm	
	Concrete Block	240 mm	
	Cement mortar	20 mm	
Internal wall	Cement mortar	20 mm	1.50
	Lightweight concrete board	100 mm	
	Cement mortar	20 mm	
Floor	Cement mortar	50 mm	0.25
	Moisture barrier	10 mm	
	Cast-in-place reinforced concrete	200 mm	
	Cement mortar	20 mm	
Slab	Cement mortar	20 mm	1.28
	Cast-in-place reinforced concrete	200 mm	
	Cement mortar	20 mm	
Roof	Cement mortar	40 mm	0.19
	Waterproof layer	10 mm	
	Cement mortar	20 mm	
	Polystyrene foam board	200 mm	
	Lightweight concrete board	100 mm	
	Cement mortar	20 mm	
External windows	Double low-e glass	14+6mm	1.79

4.1.2 Annual lighting energy consumption per unit area

According to Figure 6, the lowest value for annual lighting energy consumption per unit area is observed in Group A, which is 33.19 kWh/m^2/yr. This indicates that placing traffic spaces with lower lighting standard requirements at the climate boundaries indirectly affects the daylighting requirements of the reading areas, resulting in increased lighting energy consumption per unit area for Groups B, C, and D compared to Group A in all climate zones.

Furthermore, the simulation results show that Group B exhibits the most significant increase in annual lighting energy consumption per unit area (34.84 kWh/m^2/yr) due to its traffic and auxiliary spaces occupying the advantageous daylighting positions at the four corners of the building layout. Similarly, Groups C and D also experience a slight increase in overall annual lighting energy consumption compared to Group A in various climate zones because their traffic spaces, which require less daylighting, are positioned on the sides of the plan where have better daylighting effectiveness. The ranking of annual lighting energy consumption per unit area is as follows: Group B > Group D > Group C > Group A.

4.1.3 Annual total energy consumption per unit area and energy efficiency

As shown in Figure 7, Group A exhibits the highest value for annual total energy consumption per unit area, which is 66.79 kWh/m^2/yr. Combining this with the analysis of individual energy consumption discussed earlier, it indicates that Groups B, C, and D, by placing low-performance traffic and auxiliary spaces at the climate boundary of the building which served as buffer spaces, though leading to the increasing annual lighting energy consumption per unit area, significantly reduce the annual heating and cooling energy consumption per unit area, effectively compensating for and reducing the overall energy consumption.

Group B demonstrates the most noticeable reduction in annual total energy consumption per unit area, which is 64.31 kWh/m^2/yr, corresponding to an energy efficiency of 3.71%. Similarly, Group C experiences a significant decrease in annual total energy consumption per unit area across various climate zones, with a value of 65.07 kWh/m^2/yr and an energy efficiency of 2.58%. The ranking of annual total energy consumption per unit area is as follows: Group A > Group D > Group C > Group B, while the ranking of energy efficiency is as follows: Group B > Group C > Group D > Group A.

4.2 Energy consumption analysis of atrium space configurations

4.2.1 Annual heating and cooling energy consumption per unit area

As depicted in Figure 8, the large atrium space is configured as Groups E, F, G, and H, which incorporate staggered layouts, exhibiting reduced annual cooling energy consumption per unit area with comparison to Group A without staggered configurations. The airflow generated within the atrium spaces facilitates effective ventilation, aided by the pressure difference between the interior and exterior spaces that induces air movement, thereby reducing reliance on air conditioning systems [17, 18]. The data reveals that comparing the configurations with staggered atria toward other directions, the westward-staggering Group E has the highest annual cooling energy consumption per unit area, measuring 13.64 kWh/m^2/yr, indicating a significant influence of western sun exposure. Conversely, Group H, with northern staggered atria, exhibits the lowest annual cooling energy consumption per unit area at 12.64 kWh/m^2/yr. The ranking of annual cooling energy consumption per unit area is as follows: Group A > Group E > Group G > Group F > Group H.

The groups (E, F, G, and H) with partial staggered placements of the atrium exhibit reduced annual heating energy consumption per unit area compared to the unstaggered Group A. Among them, Group G with the atrium staggered towards the south has the lowest annual heating energy consumption per unit area at 14.52 kWh/m^2/yr, indicating that the southern staggered configuration of the atrium allows for more solar radiation, resulting in a significant reduction in annual heating energy consumption. On the other hand, Group H with the atrium placed towards the north has the highest annual heating energy consumption per unit area at 15.52 kWh/m^2/yr. The ranking of annual heating energy consumption per unit area is as follows: Group A > Group H > Group F > Group E > Group G.

4.2.2 Annual lighting energy consumption per unit area

Simulation results indicate that the groups (E, F, G, and H) with partial staggered placements of the large atrium exhibit increased annual lighting energy consumption per unit area compared to the unstaggered Group A.

As shown in Figure 9, Group G with the atrium staggered towards the south has the lowest annual lighting energy consumption per unit area at 34.90 kWh/m^2/yr. Meanwhile, Group H with the atrium staggered towards the north has the highest annual lighting energy consumption per unit area at 36.12 kWh/m^2/yr. The annual lighting energy consumption per unit area is slightly lower in Group E with western staggered atrium compared to Group F with eastern staggered atrium. The ranking of annual lighting energy consumption per unit area is as follows: Group H > Group F > Group E > Group G > Group A.

4.2.3 Total energy consumption per unit area and energy efficiency

In a comprehensive analysis, the groups (E, F, G, and H) with staggered placements of the atrium exhibit lower annual total energy consumption per unit area compared to the unstaggered Group A. This indicates that partial staggered placements of the atrium, though leading to an increase in lighting energy consumption per unit area, exhibit more significant reduction in annual heating and cooling energy consumption, compensating for the increase in lighting energy consumption resulted by disadvantageous elements. As shown in Figure 10, among the groups with staggered atrium placements, Group G has the lowest annual total energy consumption per unit area at 62.89 kWh/m^2/yr, with the corresponding energy efficiency of 5.84% at the highest.

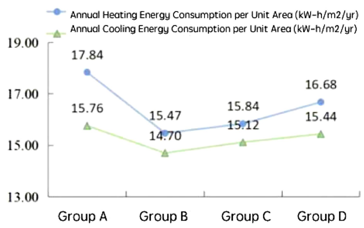


Figure 5 Heating and cooling energy consumption of variable groups in reading spaces

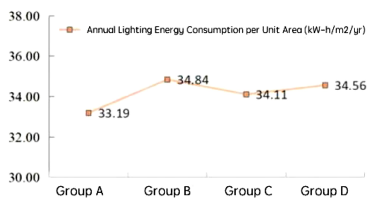


Figure 6 Lighting energy consumption of variable groups in reading spaces

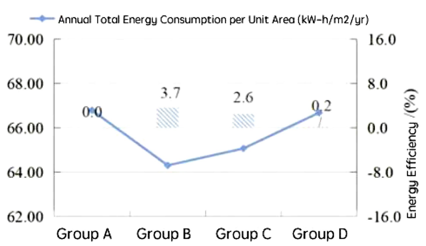


Figure 7 Total energy consumption and energy efficiency of variable groups in reading spaces

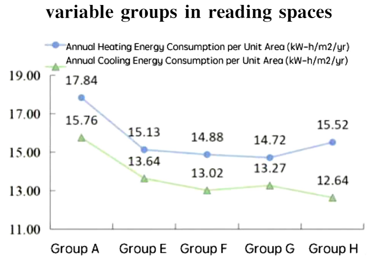


Figure 8 Heating and cooling energy consumption of variable groups in atrium spaces

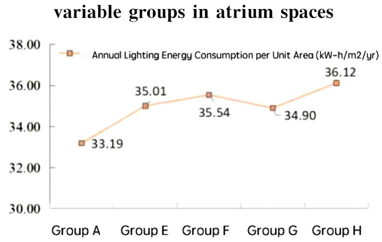


Figure 9 Lighting energy consumption of variable groups in atrium spaces

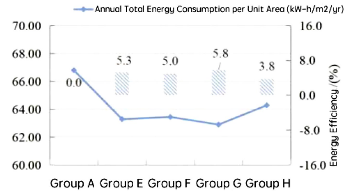


Figure 10 Total energy consumption and energy efficiency of variable groups in atrium spaces

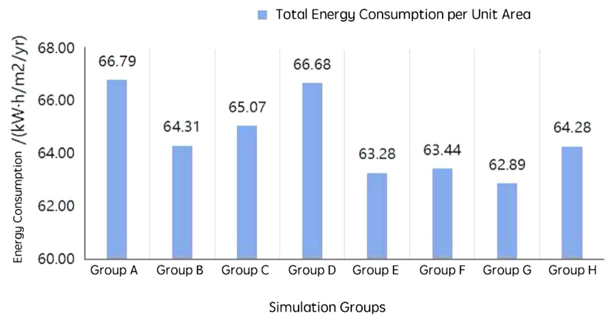


Figure 11 Total energy consumption for simulation groups

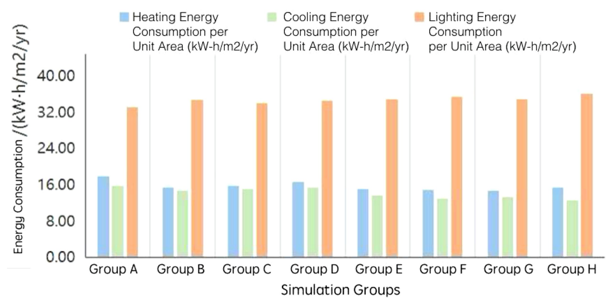


Figure 12 Individual energy consumption for simulation groups

Conclusion

Based on case studies of existing university library architectural designs, representative prototypes of overall spatial forms were extracted for simulation. By altering the organizational patterns of high-performance reading spaces and the partial staggered orientations of large atrium spaces, eight spatial organizational patterns were proposed and simulated calculations were conducted in cold climate regions, leading to the following conclusions:

Among the four combinations of variables for reading spaces, the overall energy consumption is the lowest, and the energy efficiency is the highest (reaching 3.71%) for the composite reading spaces. The overall energy consumption is comparable for the parallel reading spaces and the surrounding reading spaces, with the surrounding reading spaces having the highest overall energy consumption. The energy efficiency rankings for the four reading patterns are as follows: composite form> dispersed form> parallel form> surrounding form.

The groups with partial staggered placements of the atrium, comparing to the unstaggered-atrium group, see a decrease in overall energy consumption to some extent, and among the four combinations of variables for the atrium space, the overall energy consumption is the lowest and the energy efficiency is the highest (reaching 5.84%) for the structure form with partial staggered placement towards the south side of the atrium, while the energy efficiency is the lowest for the staggered placement towards the north side of the atrium. The energy saving rates for the atrium space variable groups are all higher than those for the reading space variable groups, indicating that the vertical staggered arrangement of the atrium has a greater impact on the overall energy consumption of the building compared to the horizontal arrangement of the reading spaces.

Based on the simulation findings mentioned above, during the early stage of schematic design, it is advisable to position low-performance spaces such as traffic and auxiliary spaces at the building perimeter, creating a buffer zone similar to transition spaces to mitigate the negative impact of external adverse climatic conditions on the internal spaces [19]. Additionally, it is recommended to consider a partial staggered design for tall and spacious central atria, with priority given to positioning the atrium on the south side. This approach not only contributes to reducing the overall energy consumption of the building and achieving energy-saving goals but also enhances the diversity of the vertical profile, enriching the spatial experience within modern university libraries.

Figure and table sources

All figures and tables in this study were created by the author.

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