Numerical Investigation of key design parameters impact on energy consumption of commercial complex distributed atrium in cold area of China

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Abstract. The high energy consumption of atrium in cold area is prominent. Both single and distributed atriums have been widely employed in commercial complex buildings, while their energy consumption performance and mechanism are not the same. Currently, far too little research has been carried out over energy-saving design of distributed atrium. In this study, the typical representative archetypes of distributed atrium, including chessboard, peripheral, series and road network types, have been numerically investigated. Through the energy consumption simulations, the impact and impartance of various design parameters such as proportion, height, plane layout, has been examined. Atrium proportion, height, general layout, aggregation and uniformity can be accounted as the key design parameters of the distributed atrium design. The simulation results that with the increase of the volume of atrium, the unit energy consumption increases. Compared with other types, the surrounding atrium is more energy-saving. With the improvement of plane uniformity of atrium, the total energy consumption of building increases. This study can provide valuable reference for the design of distributed atrium in cold area.

1. Introduction
Due to the fast urbanization process in China, a large number of commercial complex with atriums are built in the first and second tier cities in China. As the core public space, the atrium space plays a very important role in the commercial complex. It affects not only the shape, use feeling and commercial vitality, but brings also the cost of higher total energy consumption of the building.

However, through the design of atrium spaces, the energy consumption is not yet well considered, with large volume spaces commonly employed. Because of the large volume, the built environment of the atrium space can easily got affected by severa external environment, resulting in very high energy consumption of environmental regulation. In recent years, abundant newly built commercial buildings with large atrium space in unreasonable design has caused huge waste of energy.

Specifically, more and more of them start to be designed and constructed in form of distributed atriums. Comparing to single independent atrium, the energy consumption mechanism of distributed atrium is more complex. Up to now, the corresponding understanding of its key design parameters and energy-saving design strategies are quite limited.

In the aspect of commercial building research, the 2012 article of buildings, taking the selling space of commercial buildings as the research object, taking the different ways of lighting and ventilation,
building orientation, building window wall ratio, space scale and other variables as variables, multiple
groups of comparative experiments are set up, and finally the energy-saving effect of natural lighting
is more significant. Daniel Schulz focuses on the whole process of commercial complex design from a
macro perspective, and discusses its location selection, development and utilization, operation
management, decoration design and other aspects. In the research of atrium space, A. Laouadi and
other scholars quantitatively studied atrium energy consumption. In this paper, the layout of atrium,
the form of skylight, space interface, transparent area and other elements closely related to atrium are
extracted, and the relationship between them and energy consumption is studied with the help of
simulation software. Weinhold studied the influence of the sun shading system on the energy
consumption of the atrium facade. Pan et al. Used the energy plus and CFD model to study the cooling
energy consumption of the atrium. Xu Lei et al. Studied the composition factors and energy
consumption characteristics of atrium space shape. Lin Bolong put forward strategies from the
aspects of lighting, ventilation and energy application, so as to reduce energy consumption. Zhang
Qi studies the large space such as sharing, and analyzes the layout, scale and interface of the shared
space from the physical environment and energy consumption. A. Aldawoud study the thermal
performance of various shapes and geometries of atriums in buildings is exam-ined under various
conditions. The solar radiation that penetrates the atrium skylight significantly affects the thermal
environment.

Up to now, the researches on distributed atrium are still quite limited. The essential understanding
of the relationship between its key design parameters and energy consumption are urgently wanted. In
this study, the key design parameter impacts of distributed atriums in typical typologies have been
numerically investigated. The research outcomes can provide valuable information for energy-saving
design of distributed atriums.

2. Research Methodology

Firstly, the main archetype typologies of distributed atriums in commercial complex were extracted
and summarised from the case studies, in both plan volume and section plan layout.

Afterwards, the simulation configurations including the climate conditions, envelope properties,
HVAC setting and operational schedule etc have been set up.

Further, through numerical simulations, the impact of the varying atrium variables over the energy
consumption of commercial complex have been studied from several aspects: Atrium volume, atrium
layout, atrium uniformity and atrium aggregation. The key design parameters of the distributed
atriums therefore have been determined.

The overall research methodology process is as illustrated in figure 1.
2.1. Design prototype of distributed atrium space

Through investigation, it is found that most commercial complexes are distributed atrium, and the horizontal layout of the distributed atrium is complex. At present, there is no unified division for the distributed atrium. Therefore, referring to the division of a single atrium, the distributed atrium is divided into the following categories.

Of course, the actual cases are often not strict use of a combination, but comprehensive use. As a research, we need to fully understand the characteristics of each combination mode, and then predict the results of comprehensive use.

Table 1. Classification of horizontal layout of distributed atrium

| Distributed atrium | Plane sketch | Model | Atrium characteristics | Plan reference drawing |
|--------------------|--------------|-------|------------------------|-----------------------|
| Checkerboard style | ![Checkerboard](image) | ![Model](image) | The center is strong, and the atrium is less affected by the outside world | ![Drawing](image) |
| Peripheral type    | ![Peripheral](image) | ![Model](image) | Abundant building facades reduce the energy consumption of building daylighting | ![Drawing](image) |
| Series type        | ![Series](image) | ![Model](image) | The atrium has larger daylighting area and stronger spatial mobility | ![Drawing](image) |
| Road network type  | ![Road network](image) | ![Model](image) | The atrium is more distributed and more spacious | ![Drawing](image) |

2.2. Modelling configuration

The combination of online research and field research is adopted. Collect the architectural form, number of floors, height, length and width of atrium, height, form, location, interface form, material, etc. of commercial complex. Through the deletion and selection of the commercial complex in the city, 55 commercial complexes are finally studied, more than 100 typical atrium spaces are obtained, and the atrium space sample database of the commercial complex in the cold area is drawn. The proportion of atrium space is the main parameter in this simulation. When calculating the proportion of atrium space, for the case with detailed plane information, calculate the area, count the first floor area of atrium space and the first floor area of building, and get the proportion of atrium area. The results show that the proportion of atrium area is mainly between 8% and 15%. According to the investigation and classification of commercial complex, it is found that the ratio of length to width of commercial complex is 1:2. The building area of commercial complex is mainly between 100000-140000 square meters, with 6 floors and an average floor height of about 5.5m.

For the convenience of calculation and modeling, the length and width of the building and the atrium are rounded. The final standard model is determined as follows: the building is 192m long and 100m wide; the number of floors is 6 above the ground and 1 underground; the height of the building is 5.5m; the total height of the building is 33m. According to the above summary, the building standard model settings are as follows:
Table 2. Model size

| Total building area | Length and width of building | Atrium area | Length width ratio of atrium | Layer number | Total height | Storey height |
|---------------------|-----------------------------|-------------|-----------------------------|-------------|--------------|--------------|
| 124600 m²           | 100x192m                    | 2450 m²     | 2:1                         | B1-F6       | 33m          | 5.5m         |

2.3. Simulation software and calculation configurations

In this paper, the energy consumption simulation software designbuilder is selected for the energy consumption simulation experiment. Designbuilder is a simulation software developed based on the energy plus program. After the completion of the building modeling, it can be used to simulate the overall energy consumption of the building in a period of time (such as a year) after the initial data of the temperature and lighting of each functional space of the commercial building are defined in advance. The total energy consumption of buildings including lighting system, DHW, HVAC, etc. is obtained, which can help architects to realize the energy-saving optimization of building schemes, determine the appropriate energy-saving strategies, or select the best energy-saving scheme in the comparison of multiple schemes.

This paper focuses on the comparative study of simple models of commercial buildings, which is universal. Therefore, the parameters are properly modified on the basis of the parameters of the design builder software. According to the design standard for energy conservation of public buildings (GB50189-2015) and the design standard for daylighting of buildings (GB 50033-2013), the operation standards of commercial buildings are set to set the ventilation capacity of indoor personnel, the heat output of lighting and other equipment, the air conditioning temperature and the opening time.

Table 3. Material and parameters

| Name          | Material                                                                 | K and SHGC       | Specification requirements |
|---------------|---------------------------------------------------------------------------|------------------|---------------------------|
| Exterior wall | Cement mortar (20.00mm) + Extruded polystyrene (XPS) (60.00mm) + Concrete block (200.00mm) + Lime cement mortar (20.00mm) | K=0.362, K≤0.5   |                           |
| Roofing       | Cement mortar (20.00mm) + Waterproof layer (10mm) + polystyrene (EPS) (150.00mm) + Reinforced concrete slab (100.00mm) + whitewashing (20.00mm) | K=0.237, K≤0.45  |                           |
| External windows | Double layer Low-E glass 3mm colourless + 13mm A + 3mm colourless; Window wall ratio 0.1 | K=1.798, SHGC=0.595, K≤3 |               |
| Skylight      | Double layer Low-E glass                                                 | K=1.8, SHGC=0.44, K≤2.4, SHGC=0.44 |               |

3. Results and discussion

3.1. Atrium area proportion

According to the summarized survey of case studies, the proportion of atrium area is set within the range from 6.5% to 21%. Table 4 shows that the length width ratio of atrium is kept at 2:1, and the chessboard typology based distributed atrium has been adopted for the simulation investigations. In order to simplify the model and reduce the impact of other factors, the distributed atrium mode in four numbers was adopted. The modelling details are as follows:

3.1.1. Simulation scheme. The chessboard style keeps the relative positions of four atriums near the four inner corners unchanged.
### Table 4 Simulation scheme of the relationship between area proportion and energy consumption of distributed atriums

| Atrium type       | Number | Atrium area (m²) | Atrium length and width (m) | Atrium area ratio | Model |
|-------------------|--------|------------------|-----------------------------|-------------------|-------|
| Checkerboard style| CA1-1  | 1250             | 25x12.5                     | 6.510%            |       |
|                   | CA1-2  | 1800             | 30x15                       | 9.375%            |       |
|                   | CA1-3  | 2450             | 35x17.5                     | 12.76%            |       |
|                   | CA1-4  | 3200             | 40x20                       | 16.67%            |       |
|                   | CA1-5  | 4050             | 45x22.5                     | 21.09%            |       |

3.1.2. Simulation results and analysis. The simulation results as shown in figure 2 illustrates that with the increase of the proportion of atrium area, the total energy consumption of building lighting, heating and building decreases, and the total energy consumption of building refrigeration increases. For unit energy consumption, with the increase of atrium area, both the total and separate (heating and cooling) energy consumption shows an upward trend. This could be due to the fact that, with higher proportion of atrium area more heat is gained in summer and dissipated in winter through larger atrium skylights.

![Figure 2. Energy consumption with changing atrium area proportion.](image1)

![Figure 3. Changing trend of unit heating and unit cooling in CA1 group.](image2)

Taking CA1-3 as the standard value for comparison, the changing quantity and rate of unit heating and cooling energy consumption can be obtained and illustrated when the atrium area changes. It can be seen from figure 5 that the impact over the changing rate of atrium area on heating energy consumption is smaller than that on cooling energy consumption.

3.2. height of distributed atrium

3.2.1. Simulation scheme. The number of floors of atrium determines the size of atrium, which is an important design parameter. The number of atrium floors is set as a variable to study the change of building energy consumption.

### Table 5. Simulation scheme of the relationship between height and energy consumption of distributed atrium

| Atrium type       | Number | Atrium level | Atrium length and width (m) | Model |
|-------------------|--------|--------------|-----------------------------|-------|
| Checkerboard style| CB1-1  | 6            | 35x17.5x4                   |       |
|                   | CB1-2  | 5            | 35x17.5x4                   |       |
|                   | CB1-3  | 4            | 35x17.5x4                   |       |
|                   | CB1-4  | 3            | 35x17.5x4                   |       |
|                   | CB1-5  | 2            | 35x17.5x4                   |       |
3.2.2. Simulation results and analysis. From the CB1 group, it can be analyzed that for the total energy consumption, with the reduction of the number of floors occupied by the atrium, the total energy consumption of lighting, cooling and building are increasing, but the total energy consumption of heating is decreasing. It can be concluded that this is caused by the greenhouse effect of atrium. For the unit energy consumption, they show a decreasing trend. The change of atrium height has the greatest impact on unit heating energy consumption and the least impact on unit lighting energy consumption. The change of atrium height has the greatest impact on unit heating energy consumption and the least impact on unit lighting energy consumption. To sum up, for the core type atrium, when the plane of the atrium is unchanged, the more the number of atrium layers, the lower the total energy consumption of the building, but the higher the unit energy consumption. And the change is mainly determined by heating energy consumption. (Figure 4.)

![Figure 4. Energy consumption with changing atrium area height.](image)

3.3. distributed atrium layout

3.3.1. Simulation scheme. The distributed atrium can be divided into chessboard type, peripheral type, series type and road network type. In order to make the model more typical, the chessboard type and peripheral type atrium are divided into four parts, which can make the atrium more evenly distributed. Considering that the former standard model of atrium length width ratio is 2:1, the simulation still maintains the same ratio. At the same time, considering that the area of each atrium should not be too small, this simulation expand the atrium area to 3200 m². Table 6. shows the details.

| Number | Combination type     | Atrium area         | Model  |
|--------|---------------------|---------------------|--------|
| CC1-1  | Checkerboard style 1| 40x20x4=3200 m²     | ![Model](image) |
| CC1-2  | Checkerboard style 2| 40x20x4=3200 m²     | ![Model](image) |
| CC1-3  | Peripheral type 1   | 40x20x4=3200 m²     | ![Model](image) |
| CC1-4  | Peripheral type 2   | 40x20x4=3200 m²     | ![Model](image) |
| CC1-5  | Series type         | 3200 m²             | ![Model](image) |
| CC1-6  | road network type   | 3200 m²             | ![Model](image) |
3.3.2. Simulation results and analysis. The energy consumption data illustrates that the total energy consumption of several distributed atriums from low to high is that: peripheral type < series type < road network type < checkerboard type. In terms of lighting energy consumption, peripheral type < series type < road network type < checkerboard type. The reason for this is that the surrounding atrium has a larger daylighting surface, so its daylighting energy consumption is the lowest; while the chessboard layout only have daylighting by skylight, its daylighting energy consumption is the highest. For cooling energy consumption, chessboard type < road network type < series type < peripheral type; for heating energy consumption, peripheral type < series type < road network type < chessboard type. For different types of distributed atrium, they have the opposite trend for the cooling energy consumption and heating energy consumption change, but they have the same trend for the change of lighting energy consumption and heating energy consumption. (Figure 5.)

Figure 5. CC1 energy consumption change chart

3.4. spatial aggregation of distributed atrium

3.4.1. Simulation scheme. Firstly, Change the number of atrium when the total area of atrium and the ratio of length to width of atrium remain unchanged. Study the influence of the number of atrium on the building energy consumption of commercial complex. Secondly, the dispersion of the two atriums is taken as the research object. In order to make the atrium more movable, it is set as a square shape with 35m length of the side. Make the center line of atrium coincide with the center line of building, and change the distance between atriums. study the influence of atrium distance change on energy consumption of commercial complex.

| Table 7 Simulation scheme of the relationship between plane aggregation degree |
|---------------------------------|-----------------|-----------------|-----------------|
| Number | Number of atrium | Atrium length and width (m) | Model |
|--------|-----------------|-----------------|-----------------|
| CD1-1  | 2               | 24.75x49.5x2    | ![Model](image) |
| CD1-2  | 4               | 17.5x35x4       | ![Model](image) |
| CD1-3  | 6               | 14.29x28.58x6   | ![Model](image) |

| Number | Distance between the midpoint of two atriums | Model |
|--------|----------------------------------------------|-------|
| CD2-0  | 35m                                          | ![Model](image) |
| CD2-1  | 70m                                          | ![Model](image) |
| CD2-2  | 105m                                         | ![Model](image) |
| CD2-3  | 140m                                         | ![Model](image) |

3.4.2. Simulation results and analysis. The first group of data: atrium area when the total area of atrium is fixed, the number of atrium is from 2 to 6, and the change of the number of atrium brings about no obvious change in energy consumption. The second group of data: with the increase of atrium space, the total energy consumption per unit of building is increasing, but the increasing degree is more and more gentle. In the energy
consumption of subprojects, with the reduction of atrium aggregation, the energy consumption of lighting and refrigeration increases, and the energy consumption of heating decreases.

### Table 8. The relationship between plane aggregation and energy consumption (kwh/ m²)

| Number | Total building area (m²) | Unit lighting consumption | Unit Cooling consumption | Unit Heating consumption | Unit Total consumption |
|--------|--------------------------|---------------------------|-------------------------|-------------------------|------------------------|
| CD1-1  | 122150                   | 36.35                     | 68.89                   | 56.51                   | 161.75                 |
| CD1-2  | 122150                   | 36.39                     | 68.9                    | 56.5                    | 161.79                 |
| CD1-3  | 122150                   | 36.36                     | 68.88                   | 56.51                   | 161.75                 |
| CD2-0  | 122150                   | 35.83                     | 68.71                   | 56.55                   | 161.09                 |
| CD2-1  | 122150                   | 36.26                     | 68.84                   | 56.53                   | 161.63                 |
| CD2-2  | 122150                   | 36.39                     | 68.91                   | 56.49                   | 161.79                 |
| CD2-3  | 122150                   | 36.4                      | 68.91                   | 56.49                   | 161.8                  |

#### 3.5. uniformity of distributed atrium

3.5.1. Simulation scheme. The volume of the two atriums of the standard model is changed, the proportion of the two atriums is changed, and the influence of the uniformity of the atrium space on the energy consumption is discussed. In addition, we take the chessboard type and peripheral type atrium as the research object, and set up the simulation scheme.[11]

### Table 9. Simulation scheme of the relationship between the plane uniformity of atrium and energy consumption

| Number | Proportion | Atrium type | Model |
|--------|------------|-------------|-------|
| CF1-1  | 1:1        | Checkerboard style | ![Checkerboard style](image) |
| CF1-2  | 1:2        |             | ![Checkerboard style](image) |
| CF1-3  | 1:3        |             | ![Checkerboard style](image) |
| CF1-4  | 1:7        |             | ![Checkerboard style](image) |
| CF1-5  | 2:1        |             | ![Checkerboard style](image) |
| CF1-6  | 3:1        |             | ![Checkerboard style](image) |
| CF1-7  | 7:1        |             | ![Checkerboard style](image) |

| Number | Proportion | Atrium type | Model |
|--------|------------|-------------|-------|
| CF2-1  | 1:1        | East West   | ![East West](image) |
| CF2-2  | 1:2        | Peripheral  | ![Peripheral](image) |
| CF2-3  | 1:3        |             | ![Peripheral](image) |
| CF2-4  | 1:7        |             | ![Peripheral](image) |
| CF2-5  | 2:1        |             | ![Peripheral](image) |
| CF2-6  | 3:1        |             | ![Peripheral](image) |
| CF2-7  | 7:1        |             | ![Peripheral](image) |

3.5.2. Simulation results and analysis. For chessboard type atrium, with the increase of the proportion difference of atrium area, the building unit energy consumption is lower and lower, the unit lighting energy consumption and heating energy consumption are lower and lower, and the cooling energy consumption is higher and higher.
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Figure 6. CF1 group energy consumption change chart

For the peripheral atrium in the east-west direction, with the increase of the proportion difference of atrium area, the energy consumption per building unit is not more and more low, and the trend of energy consumption change is complex. The trend of unit lighting energy consumption and heating energy consumption is also complex, lacking certain regularity.

Figure 7. CF2 group energy consumption change chart

The influence of evenness on chessboard style is greater than that of peripheral style. Therefore, the study of the uniformity of atrium is more meaningful for the chessboard type atrium. That is to say, the regularity of evenness and energy consumption changes in atrium is more obvious only when skylight is used and side windows are not used. This is because, according to the above research on layout, when the atrium has side windows for lighting, the direction will have a greater impact on energy consumption.

4. Conclusion

The simulation results that with the increase of the volume of atrium, the total energy consumption decreases, but the unit energy consumption increases. Among the examined various layout typologies of distributed atrium, the peripheral style is relatively more energy-efficient. With the increase of atrium plane aggregation degree of commercial complex, commercial complex is more energy-saving. With the increase of plane uniformity of atrium in commercial complex, the building consumes more energy.

In this study, the key design parameter impacts of distributed atriums in typical typologies have been numerically investigated. Atrium volume, atrium layout and atrium aggregation can be accounted as the key design parameters of the distributed atrium design. The main conclusions of this work can be summarized as follows:

To conclude, for designing distributed commercial atrium in cold area of China, firstly, appropriate volume with rational area and height should be determined according to the use requirements. Unnecessary excessive volume must be avoided. Secondly, proper plan layout exhibits as effective method to reduce energy consumption. The appropriate employment of the surrounding layout can well reduce the lighting energy consumption. Finally, For chessboard type atrium, the plane aggregation level should be enhanced, while the uniformity level should be reduced to control the total energy consumption.

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