Abstract
The occupant-centric control is one of the important concepts in buildings. For some public spaces, in which occupants are highly mobile, the traditional control method has encountered the problem of unnecessary energy consumption and localized thermal discomfort. Therefore, this paper takes an exhibition hall as the main research object and carries out the research of occupant-centric control. By means of field measurements and simulations, this study proposes two control strategies and verifies their effectiveness. The results show that the temporal modulation and spatial modulation enable the exhibition hall to achieve 38.8% and 45.2% daily heating consumption reduction respectively and the latter one results in a more uniform distribution of indoor PMV values. They achieve a reduction in building energy consumption while improving human thermal comfort, and provide a reference for other occupant-centric control in similar buildings or spaces.

Highlights
The characteristics of the occupant displacement in exhibition hall were summarized.
Proposing two control strategies, namely temporal modulation and spatial modulation.
The effects of two control strategies were well evaluated through simulation.
Strategies achieved heating consumption reduction and thermal comfort improvement.

Introduction
Under the background of achieving carbon peaking and carbon neutrality goals, the issue of how to achieve reasonable regulation of the building environment according to occupants’ needs and minimize building energy consumption has raised wide attention. It shows that the occupant-centric control (OCC) is one of the important concepts to simultaneously meet human comfort and achieve energy saving in buildings (O'Brien et al., 2020). The OCC method usually consists of three objects, which are the indoor environment, the occupants, and the building systems. The common process of OCC is collecting indoor environment parameters and the occupants' behavior by various sensors, inferring the effect such as comfort and efficiency of the occupants, and sending the optimal control actions to the building systems (Park et al., 2019). The OCC enables a shift from the traditional maintenance of stationary environment to adapting to occupants needs, which increases user satisfaction and even the usability of the building spaces (Huizenga et al., 2006). A review has shown that OCC can achieve 22% energy savings and 29.1% comfort improvement (Xie et al., 2020). Therefore, the widespread application of OCC in buildings has great potential for energy savings (Pang et al., 2020).

Due to the different characteristics of occupant behavior in different types of buildings, the research on OCC methods needs to clarify the corresponding control methods according to the specific building types and their characteristics (Park et al., 2019). The current researches on OCC mainly focus on building types like office buildings (Jung & Jazizad, 2019; Konis et al., 2020), laboratories (Zhong & Choi, 2017), and hotels (Pang et al., 2021), in which controlled objects are usually HVAC systems (Jung & Jazizad, 2019; Zhong & Choi, 2017) and shading systems (Tabadkani et al., 2021) in buildings. For example, Jung and Jazizad (2019) adjusted the temperature set point of the HVAC system in an office building according to the user's personalized thermal comfort preference, achieving a system energy saving of up to 25%. Zhong and Choi (2017) performed modulation of a central AC system in a laboratory under the guidance of occupants thermal comfort prediction which is calculated by an artificial intelligence algorithm, and the results showed an energy saving of up to 45% and a thermal comfort performance improvement of up to 44.3%.

Currently, the OCC researches are mainly conducted in spaces where the location of occupants is static and predictable. However, for some public spaces with high personnel mobility, such as airports, railway stations, museums, exhibition halls, and some large foyers, there is a lack of relevant research on OCC. Such public spaces are characterized by random occupant displacement, high movement frequency, and uncertain location (Han et al., 2022; Tabak et al., 2010), leading to significant differences in occupants behavior from the previously areas. Therefore, the OCC methods in such public space need further research, which cannot be directly borrowed from the existing researches.

In the public space mentioned above, traditional control methods are mainly developed from the perspectives of equipment selection and equipment efficiency improvement (Zhang et al., 2015), optimization of
equipment system operation strategy (Yildiz et al., 2022), or available passive energy efficiency practices (Xu et al., 2005). These control methods usually take the whole building space as one controlled object and synchronize all the equipment in the building to achieve a uniformly comfortable environment in the space. It is easy to find from the control concepts that these traditional control methods do not pay sufficient attention to the characteristics of occupants activities in such large spaces, and therefore will lead to problems in environmental thermal performance and energy use. The traditional control method pursues the uniform comfort of the whole large space. But the fact is that not the entire space is the main activity area caused by occupants preference. It leads to a mismatch between environmental supply and personnel demand, resulting in unnecessary energy consumption and the problem of local discomfort (Ono et al., 2022).

Therefore, this paper takes an exhibition hall as the example research object and starts the research of OCC method, aiming to provide sufficient attention to occupants behavior and optimize the control of the equipment in the exhibition hall from the temporal and spatial perspectives. Firstly, based on the field measurement, the temporal and spatial characteristics of the occupant displacement are summarized. Then, according to the occupancy rate, this study proposes a temporal modulation method, which achieves hourly optimal control at working time from a temporal perspective. Further, a spatially optimized modulation method was also applied in this study, namely spatial modulation to solve the problem of local thermal discomfort and energy waste. To predict the effects of these two modulation methods, a physical model was developed and calibrated. Based on the calibrated model, the effectiveness of the proposed two modulation strategies is quantitatively evaluated by exploring the indoor temperature, energy consumption and average PMV obtained from the simulations. This study fills a gap in research on energy saving and improving people's comfort in such public buildings and provide references in other buildings or spaces with similar characteristics.

In the next section, the detailed descriptions of the field measurement, optimized modulation and simulation settings are presented in section Methodology. In section Result and analysis, the occupant displacement characteristics together with prior control areas, model calibration results, and the effects of the temporal modulation and spatial modulation are presented. The main finding of this research is summarized in section Conclusion.

**Methodology**

The technical approach is shown in Figure 1. Firstly, a typical exhibition hall in severe cold region of China during the winter heating period is selected as the research object. Through field measurement, information includes building layout, heating equipment operation data, indoor and outdoor thermal environment data, and occupant displacement data, et al. were obtained. The indoor and outdoor thermal environment data include indoor temperature under multi-use scenarios and simultaneous outdoor temperature. The occupant displacement data are collected mainly on working day, weekends and holiday. Based on the temporal and spatial characteristics of occupant displacement in the exhibition hall, the prior control areas were identified. Meanwhile, the thermal environment model of the exhibition hall is established based on the measured data. Model calibration is carried out by comparing the measured and simulated temperature in two cases. Finally, this study proposes two modulation methods for the indoor heating equipment in exhibition hall from the temporal and spatial perspectives. The effect of the modulation strategies were compared and evaluated by temperature, hourly load, daily energy consumption and average PMV.

![Field measurement 1](https://doi.org/10.26868/25222708.2023.1706)

**Field measurement**

1) Basic information

The typical exhibition hall in this study located in a suburb of Zhangbei County, Zhangjiakou City, Hebei Province, a severe cold region of China. The exhibition hall is 10.8*10.8*4.2m in length, width and height, consisting of the main room, two foyers, one restroom and one equipment room. The main room of the exhibition hall is a large open space, with one column in the southwest and one in the northeast. Two foyers are located in the southeast and northwest corners of the exhibition hall, and southeast foyer is adjacent to the equipment room and the restroom. The study is mainly carried out in the main room, which is equipped with two kinds of heating equipment: wall radiators and skirting heaters. Four wall radiators are installed on the southeast inner wall, each with the size of 0.8m*1.8m. Their design water temperature of the heat pump is 55°C and the heating capacity is 16kW. Six skirting heaters are located on the
south and north side of the main room near to the window, with the equipment size of 1105*122*179mm and the rated power of 2200W.

2) Measurement
The data of indoor air temperature, wall temperature, heating equipment surface temperature and outdoor temperature were collected every minute from November 22 to November 28, 2021. During these days, the heating equipment were controlled to be on and off. The information of each measurement point and instrument are shown in Table 1 below. A total of 26 measurement points is arranged as shown in Figure 2. There are 15 indoor air temperature points, as shown in Figure 3 (a), of which A1~A13 are set at a height of 1.0m from the ground. Two points B5 and C5 are located in the center of the main room. The heights are from the ground 2.0m and 3.0m respectively. Through these 15 indoor temperature measurement points, the temperature distribution of the main room is obtained. There are 4 wall temperature measurement points, W1~W4, as shown in Figure 3(b), which stick to the glass surface of the north and south side and the wall surface of the east and west side, respectively. In order to obtain the actual temperature data of the heating equipment, one temperature measurement point S was set on the surface of the wall radiator, shown in Figure 3(c), and four temperature measurement points S1~S4 were set on the top of skirting heaters, shown in Figure 3(d). Meanwhile, two outdoor temperature measurement points were located at the shadows of the south and north sides of the building.

Table 1: Information of the measurement point and instruments.

<table>
<thead>
<tr>
<th>Point</th>
<th>Data collected</th>
<th>Instrument</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1~A13, B5, C5</td>
<td>Indoor air temperature</td>
<td>Temperature and humidity self-recording instrument</td>
</tr>
<tr>
<td>W1~W4</td>
<td>Indoor wall temperature</td>
<td>Range: -30°C ~70°C, Accuracy: 0.5°C, Resolution: 0.1°C</td>
</tr>
<tr>
<td>S, S1~S4</td>
<td>Near-surface air temperature of Heater</td>
<td>-20°C ~40°C, the rest 1.0°C,</td>
</tr>
<tr>
<td>South and north point</td>
<td>Outdoor shaded temperature</td>
<td>Bluetooth location beacon, Spatial resolution: 0.5°*0.5m, Signal reception time: 1.0s</td>
</tr>
<tr>
<td>P1~P22</td>
<td>Personnel displacement</td>
<td></td>
</tr>
</tbody>
</table>

The occupancy was measured by the number of people appeared in exhibition hall. The number of people appeared in the hall were recorded by Bluetooth location beacons, which monitored the positioning data sent by Bluetooth on occupants’ cell phones every second. Through counting all the displacement points in one hour, the cumulative occupancy of the exhibition hall was obtained. This monitoring was conducted from 10:00 am to 11:00 am on working day, weekend and holiday respectively. The location of the 22 Bluetooth location beacons is shown in Figure 2, and their information are shown in Table 1.

Figure 2: Measurement point setting.

(a) Indoor air temperature points

(b) Wall temperature points

(c) Wall radiator points

(d) Skirting heater points

Figure 3: Test site photos.

Optimized control strategy
The common working hours of the exhibition hall are generally 8:00-18:00. From temporal perspective, the change of external temperature during a day is one of the main factors affecting the thermal environment in the exhibition hall in winter. This study proposes a temporal modulation method according to the external temperature and occupancy rate, which achieves hourly optimal control at working time. The flow chart of temporal modulation is shown in the Figure 4. The heating power of all skirting heaters is regulated with choices of 100%, 75%, 50%, 25% and 0% simultaneously. At each moment, the PMV values of the indoor occupant activity area are obtained by simulation and the power is adjusted. If the PMV value is in the thermal comfort range (±1.1), this operating power is selected as the final optimized solution for that time period. If the PMV value is not in the comfort range, the PMV value is adjusted by the external temperature, and the power is optimized. The PMV value is obtained by simulation, the simulation software is PMV 7.0, and the simulation process is completed by natural environmental parameters of the exhibition hall. The simulation results are shown in Table 2.
range, the power of all skirting heaters is increased or decreased simultaneously until the PMV value reaches the comfort range or the heater power reaches the limit.

Further, a spatially optimized modulation method was also applied in this study, namely spatial modulation to solve the problem of local thermal discomfort and energy waste. The flow chart of the spatial modulation is shown in Figure 5. The main room is divided into five prior control areas according to the characteristics of indoor occupants’ displacement. Each key area is controlled separately. Therefore, different from the temporal modulation, the heater in each area can be adjusted respectively according to the specific situation, and the power of each radiator can be different. For each prior control area, at each moment, the power of the skirting heater will be selected until the PMV value of the area reaches the comfortable range or the heater power reaches the limit.

**Simulation**

The building thermal environment model for this study is built based on AirPak, and version 3.0.16 is used in this study.

1) Basic model

Based on the field measurement, the geometry model of this exhibition hall in AirPak is appropriately simplified as shown in Figure 6. The thermal parameters of the envelopes are shown in Table 2.

**Table 2: Model thermal parameters settings.**

<table>
<thead>
<tr>
<th>Location</th>
<th>Heat transfer coefficient W/(m²·K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>East and west</td>
<td>0.308</td>
</tr>
<tr>
<td>External walls</td>
<td>0.280</td>
</tr>
<tr>
<td>North and south</td>
<td>0.547</td>
</tr>
<tr>
<td>Interior walls</td>
<td>Insulation</td>
</tr>
</tbody>
</table>

2) Model calibration

Two cases were set up for calibration, namely full heat at night and partial heat at day, as shown in Table 3. The measured outdoor average temperature is taken as the input and the simulated indoor temperatures are compare with the measured data to verify the accuracy of the model.

**Table 3: model calibration cases.**

<table>
<thead>
<tr>
<th>No.</th>
<th>Name</th>
<th>Setting</th>
<th>Input</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Full heat at night</td>
<td>Night, turn on all skirting heater and wall</td>
<td>November 27, 2021, 0:00-1:00 outdoor average temperature and equipment status</td>
</tr>
<tr>
<td>2</td>
<td>Partial heat at day</td>
<td>Day, turn on all wall radiators and some skirting heaters</td>
<td>November 24, 2021, 10:00-11:00 outdoor average temperature and equipment status</td>
</tr>
</tbody>
</table>

3) Study cases

In order to evaluate the effectiveness of the proposed OCC strategies, based on the calibrated model, three study cases are set up and shown in Table 4. The outdoor...
meteorological parameters used in these cases were obtained from the CSWD dataset for Zhangbei City, Hebei Province from 8:00-18:00 on January 1st.

Table 4: Simulation cases for three modulation methods.

<table>
<thead>
<tr>
<th>No.</th>
<th>Name</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Traditional control strategy</td>
<td>All skirting heaters run at 100% power</td>
</tr>
<tr>
<td>B</td>
<td>Temporal modulation</td>
<td>All skirting heaters run at the same time at the same power levels</td>
</tr>
<tr>
<td>C</td>
<td>Spatial modulation</td>
<td>Skirting heaters are running at different power levels separately</td>
</tr>
</tbody>
</table>

Result and analysis

Occupant displacement characteristics and prior control area setting

In this study, the occupant displacement data was collected every 10 minutes from 10:00 a.m. to 11:00 a.m. on different typical days. The cumulative results of occupant displacement are shown in Figure 7. It can be found that the total number of displacement points in the hall of the exhibition hall on working day, weekend and holiday are 48, 124 and 182. The temporal characteristics of the occupancy density is: holiday > weekend > working day.

![Figure 7: Cumulative results of occupant displacement.](https://example.com/image1)

By superimposing the above three date maps, the general distribution of occupancy in the exhibition hall is obtained, as shown in Figure 8. It can be seen that there exist obvious gathering areas of occupancy in the main room. In this study, the above occupancy aggregation areas are further divided to five prior control areas, as shown in the blue area in Figure 8. The occupancy distribution results of each prior control area are shown in Table 5. The total area of these five important areas is 42.76 m², accounting for 47.45% of the main room area of the exhibition hall. According to the cumulative occupancy rate in Table 5, the five prior control areas cover 78.80% of the indoor occupancy distribution, and the occupancy density of the prior areas is 6.52 persons/m². Compared with 3.92 persons/m² in the hall space when the control areas were not divided, the prior control areas reflect the main characteristics of gathering occupancy, and the generalization ability of the occupancy distribution is improved by 1.66 times.

Figure 8: Prior control area based on the characteristics of occupant displacement.

Table 5: Description of the prior control areas.

<table>
<thead>
<tr>
<th>Control area No.</th>
<th>Location</th>
<th>Size</th>
<th>Cumulative occupancy rate %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.1m from the south wall</td>
<td>0.1m from the south wall</td>
<td>19.20</td>
</tr>
<tr>
<td>2</td>
<td>0.1m from the west wall</td>
<td>7.0m long, 1.2m wide, 0-2.0m high</td>
<td>16.95</td>
</tr>
<tr>
<td>3</td>
<td>0.1m from the north wall</td>
<td>0.1m from the north wall</td>
<td>18.08</td>
</tr>
<tr>
<td>4</td>
<td>0.1m from the east indoor wall</td>
<td>0.1m from the east indoor wall</td>
<td>10.45</td>
</tr>
<tr>
<td>5</td>
<td>The middle of the exhibition hall</td>
<td>The middle of the exhibition hall</td>
<td>14.12</td>
</tr>
</tbody>
</table>

Total personnel occupancy = 78.80

Model calibration

The calibration results are shown in Figure 9. The results of case 1 show that the absolute error range of the temperature of each measurement point in the room is -0.37~5.26°C, and the average absolute error of temperature is 1.22°C. The relative error range of the temperature of each measurement point is -1.39%~25.45%, and the average temperature relative error is 6.42%. This result indicates that the model can reflect the distribution of indoor temperature when the heating equipment is fully turned on at night.

The results of case 2 show that the absolute error range of the simulated and measured room temperature is -1.60~3.44°C, and the absolute error of the average temperature is -1.05°C, the relative error range of the room temperature is -6.13%~15.09%, and the relative error of the average temperature is 4.38%. This result shows that the model predicts the indoor temperature properly when the heating equipment is partially turned on during the daytime.
The above calibration results show that the model established in this study can reflect the real indoor thermal environment and can be used as the basis for further analysis.

Results of the three modulation strategies

Figure 10 shows the heating load ratio of each skirting heater during 8:00-18:00 under different control strategies. The maximum load ratio for temporal modulation and spatial modulation occurs at 8:00 at 75%, indicating that the main room does not require the skirting heaters to operate at maximum load. And as shown by the running strategies of heater 1 and heater 4 in the spatial modulation, only heater 1 and heater 4 near the inner door reach maximum load ratio while the rest of the heaters located inside the room only operate at 50% load ratio. In addition, the load ratio at 18:00 for both the temporal modulation and spatial modulation is both less than the load ratio at 8:00.

Heating consumption under the three modulation methods is shown in Figure 11. As is indicated by the heating consumption of skirting heaters in Figure 11(a), the peaking load occurs at 8:00 and they are 13.2 kW for traditional control strategy, 9.9 kW (25% reduction) for temporal modulation and 7.7 kW (41.7% reduction) for spatial modulation. As is indicated by heating consumption of all heaters (four wall radiators are also included) in Figure 11(b), the peaking load is 23.2 kW for traditional control strategy, 19.9 kW (14.2% reduction) for temporal modulation and 17.7 kW (23.7% reduction) for spatial modulation. In addition, temporal modulation and spatial modulation have presented obvious hourly heating consumption reduction between 10:00-16:00 for all heaters, especially for 13:00-15:00, the hourly heating consumption under the modulation methods for these three hours are all reduced by 60%.

The daily cumulative heating consumption of the skirting heaters in traditional control strategy, temporal modulation and spatial modulation modes are 155.2 kwh, 56.2 kWh (63.7% reduction) and 39.7 kWh (74.4% reduction). Spatial modulation results in a 29.6% reduction on daily heating consumption of skirting heaters over temporal modulation. Meanwhile, the daily cumulative heating consumption of all heaters in traditional control strategy, temporal modulation and spatial modulation modes are 255.2 kWh, 159.5 kWh (38.8% reduction) and 139.7 kWh (45.2% reduction). Spatial modulation results in a 10.6% reduction on daily heating consumption of all heaters over temporal modulation.

From the box plot of indoor average PMV in Figure 12, it can be seen that the range of PMV of traditional control strategy, temporal modulation and spatial modulation are all in the comfortable zone of slightly cool and slightly warm (PMV ∈ (-1, 1)). Compared to the average values of indoor PMV of traditional control strategy (0.268), values are slightly lower of temporal modulation (-0.468) and spatial modulation (-0.257), which is beneficial for the energy saving of the heating equipment. The total change range of PMV for traditional control strategy, temporal modulation and spatial modulation are 0.881, 0.691 and 0.206 respectively, while the ranges of 75th percentile and 25th percentile of traditional control strategy (0.302), temporal modulation (0.351) and spatial modulation (0.060) show that spatial modulation represents a maximum reduction of 82.9%. Spatial modulation significantly improves the stability of PMV, so that thermal environment more comfortable through its precise adjustment.
Conclusion

Starting from the concept of OCC, this paper takes a typical exhibition hall in the severe cold region of China as the main research object. Through the collected occupancy distribution data, the temporal and spatial characteristics of the cumulative occupancy distribution of the exhibition hall building are extracted. Under the guidance of the characteristics of occupant displacement, this research proposes two optimal modulation methods for indoor heating equipment, namely temporal modulation and spatial modulation. In order to evaluate the effect of these two modulation methods, the field measurement and model simulation are combined in this paper. A model of the exhibition hall is established in AirPak, and further model calibration work is carried out. Finally, this study analyzes the results of traditional control strategy, temporal modulation and spatial modulation. The main findings of this study are as follows:

1) The temporal characteristics of the occupancy density is: holiday > weekend > working day. For the spatial characteristics, there exist obvious gathering areas in the main room. According to the two characteristics, this research sets five prior control areas, which cover a total of 78.80% of the personnel displacement, with a unit personnel density of 6.52 persons/m². Compared with the density without prior control area, the generalization ability of the control areas on occupant displacement is increased by 1.66 times.

2) In temporal modulation, compared with traditional control strategy, the peaking load of all heaters reduces 14.2%. The reduction of hourly heating consumption of all heaters reaches 60% in maximum. The daily cumulative heating consumption of skirting heater is reduced by 63.8% and the daily cumulative heating consumption of all heaters is reduced by 38.8%. More positively, in spatial modulation, peaking load of all heaters reduces 23.7% and reduction of hourly heating consumption of all heaters also reaches 60% in maximum. The daily cumulative heating consumption of spatial modulation show a 74.4% reduction of skirting heaters and a 45.2% reduction of all heaters.

3) The ranges of indoor average PMV of three modulation methods are all in the comfortable zone of slightly cool and slightly warm (PMV ∈ (-1, 1)). The average PMV values are slightly lower for temporal modulation (-0.468) and spatial modulation (-0.257), which is beneficial for the energy saving of the heating equipment. In addition, according to the ranges of 75th percentile and 25th percentile, the spatial modulation significantly improves the stability of PMV and provide a more comfortable environment for the occupant.

The above conclusions show that two optimal modulation strategies proposed in this study are a solution to the problem of energy saving and improving human comfort in exhibition hall buildings. It is an attempt to extend the concept of OCC to such public buildings with high occupant mobility. Besides, the general optimization method of temporal modulation and spatial modulation can also be applied to buildings or spaces with similar
characteristics, even different types of buildings with different conditions, different seasons and different time periods. Since different buildings and cases have varied occupants’ behavior characteristics, there is more room for improvement in the application of the optimization method in this paper, such as collecting more personnel displacement data to establish a universal stochastic model, building an actual modulation platform to verify the strategy, using machine learning (like unsupervised algorithms and reinforcement algorithms) to further optimize the generation of control strategies. This paper provide a reference and more researches about the OCC are expected to fill those gaps.

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References