Theoretical Study on the Relationship of Building Thermal Insulation with Indoor Thermal Comfort Based on APMV Index and Energy Consumption of Rural Residential Buildings

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Featured Application: This paper proposes a new evaluation method for rural residence thermal insulation performance based on indoor thermal comfort (PMV) index, which provides a new optimization idea for the retrofitting of existing buildings.

Abstract: In the field investigation of rural dwellings, it was found that thermal feelings are significantly different with varied envelopes even under the same indoor air temperature, and this paper explores the phenomenon in simulation. Based on building thermal investigations in several villages of North China, a typical energy and environment simulation model for rural residences was developed using DeST, and the hourly parameters of temperature and humidity were used to calculate the adaptive thermal comfort (APMV) of the rooms. The results show that the main reason for the different thermal comfort at the same air temperature is the large difference in the inner surface temperature. By adjusting the insulation thickness of the envelope structure, the relationship between it and the APMV value is obtained. By adjusting the insulation thickness of the enclosure structure and getting the correlation between it and the APMV value, it is obtained that when the heat transfer coefficient of the enclosure structure meets 0.5 W/(m²·K), the indoors can be in thermal comfort. This paper considers that the indoor air temperature cannot represent the APMV to evaluate the indoor thermal comfort, and the APMV value should be used to evaluate the thermal comfort of the renovated building and calculate the corresponding energy saving rate.

Keywords: retrofitting of rural building; building insulation; energy consumption simulation; indoor thermal environment; adaptive thermal comfort

1. Introduction

At present, rural construction is a priority for the Chinese government. How to reduce the energy consumption of rural buildings and improve the happiness of farmers is one of the urgent issues that the government needs to solve [1]. According to the China building energy consumption report, buildings account for 21% of total energy consumption in China, of which rural buildings account for 24%, urban residential buildings and public buildings account for 76% [2]. China’s rural dwellings are mostly built by residents based on preferences and traditional experience rather than construction codes, and 80% have no insulation for building envelopes [3]. Most rural buildings are built at the expense of indoor comfort and energy efficiency to reduce costs, and rural residents have to pay a large sum for additional heating of uncomfortable indoor spaces. Especially in the north of China, including Beijing, Shandong, Shanxi, Shaanxi and other provinces and cities, the outdoor temperature is often below 0 °C in winter. Therefore, the heating demand
and low-level building insulation become main reasons for high energy consumption of rural building [4], and the energy consumption will continually rise as heating demand and floor area increase. Thus, how to reduce building energy consumption and increase indoor thermal comfort in rural buildings in cold areas has become the research direction of many scholars.

Homod et al. [5] used the software Ansys to simulate the energy consumption of vernacular buildings and autoclaved aerated concrete (AAC) buildings in Iraq, and the results showed that vernacular buildings had the highest energy saving potential up to 48% over 24 h a day. Hamdy and Siren [6] focused on a two-story building in Finland, based on Genetic Algorithm with IDA ICE (building performance simulation program), to obtain the optimal combination of building envelope and heating, ventilation and air conditioning (HVAC) system with minimum energy consumption and investment cost. Paola et al. [7], proposed two scenarios for retrofitting rural houses by adding internal and external insulation, and after simulations, it was obtained that there was no significant difference in the annual energy load between the two scenarios. Sengul Guven [8] selected four provinces and two different insulation materials from four different climate zones in Turkey and calculated to determine the optimal insulation thickness. Siudek et al. [9] retrofitted rural buildings in Poland by adding insulation and regenerative devices, and the results showed a significant reduction in energy consumption in the retrofitted buildings.

In China, researchers have also paid attention to this issue. Shao and Jin [10] obtained the neutral temperature and acceptable temperature ranges of rural residents in Zhalantun city through a survey, and the software Design Builder was used to calculate the optimal combination of building parameters. Zhou et al. [11] used Fluent to analyze the effect of Trombe wall (a passive ventilation technology) on the indoor thermal environment of two rural buildings in Qingdao during summer, and the results showed that Trombe wall can effectively enhance the natural ventilation and improve the thermal comfort of the buildings. In the study of Kong et al. [12], it was found that enhancing the thermal insulation of the building envelope could maintain indoor thermal comfort with relative lower supply water temperature compared to insufficient insulated building envelope, thus the energy efficiency of the air source heat pump could be improved. Hu et al. [13] conducted research on the energy-saving retrofit of a rural building of Shandong and analyzed the retrofit plan of the envelope insulation based on the cost-effectiveness. Cao et al. [14] proposed a retrofit solution for a farmhouse building in Anhui Province, and obtained a building retrofit solution from the perspectives of thermal comfort, energy saving rate and cost. The studies mentioned above show that researchers have conducted extensive research on rural building retrofits and indoor thermal comfort. The majority of them used indoor air temperature as indoor thermal comfort index to evaluate the buildings retrofitting methods, and only one mentioned PMV as an indicator. Previous studies have not considered the evaluation of building envelope retrofits in terms of indoor PMV values, and hour-by-hour calculations of the relationship between envelope and indoor PMV values in rural areas of north China. Therefore, the present study is the first to consider these characteristics.

Ashrae [15] defined thermal comfort as “the condition of the mind in which satisfaction is expressed with the thermal environment”, which is influenced by air temperature, mean radiant temperature, air relative humidity, air velocity, metabolic rate and clothing. The Predicted Mean Vote (PMV) is one of the most widely used measures for evaluating thermal comfort conditions in buildings, but rural residents have been in an uncomfortable indoor environment for a long time, they have become more adaptable to the environment, so the adaptive thermal comfort [16] theory is more appropriate to be applied in this paper.

Therefore, this paper aims to propose the evaluation of rural residential building retrofits based on thermal comfort, and obtain the relationship between them, thus providing a theoretical basis for an energy-saving building design. There are three specific objectives: (1) To explore the indoor thermal comfort of buildings without insulation and buildings with insulation at the same indoor temperature, and compare the thermal comfort difference. (2) To analyze the energy needs for space heating of insulated buildings and
compare the buildings without insulation when the indoor thermal comfort value is the same. (3) To analyze the relationship the heat transfer coefficient and the indoor thermal comfort at a certain temperature.

2. Simulation and Research Methods

The indoor thermal environment is a complex system with multiple factors interacting with each other. Therefore, computer simulations provide a more accurate way to analyze the influence of an independent parameter on indoor thermal environment and building energy consumption.

2.1. Simulation Tool

DeST is an annual dynamic energy consumption simulation software developed by Tsinghua University, which is a dynamic simulation platform for calculating building thermal processes and building energy consumption [17]. It is widely used to analyses and simulate building energy consumption in China. In the study of Zhu et al. [18], a detailed loads simulation comparison of DeST with commonly used building energy modeling programs EnergyPlus and DOE-2.1E, based on ASHARE Standard 140 tests, and the results showed that the calculation deviation is controlled within 10% which demonstrate the accuracy of DeST. To analyze the influence of the envelope insulation on the thermal comfort, DeST was used to develop the building model and calculate the indoor air temperature and internal surface temperature in this paper.

2.2. Building Description

During the field investigation of rural areas in Beijing, it was found that most of the existing rural residential buildings are two-stories. The houses are built with simple construction techniques, and some are not equipped with thermal insulation layers, and the windows are mainly made of single-layer glass. Overall, the envelope structure has poor thermal insulation and high heat transfer coefficient.

Based on the research results, this paper selects a typical building in the rural residence atlas as the simulation analysis object and Figure 1 shows the layout of the building.

![Figure 1. Layout of the research building object: (a) first floor and (b) second floor.](image)

2.3. Calculation Parameters of Building Model

To achieve a high precision of the paper’s findings, the meteorological parameters used for this simulation are based on the Chinese meteorological parameters of the Beijing area which contains the hourly temperature for 8760 h of whole year, and the specific values are in Appendix A.
Through the field investigation, it was found that all the main building envelope structures of the current rural buildings were brick walls. Combining the field investigation and Design standard for energy efficiency of rural residential buildings [19], the pre-retrofit wall was set as “20 mm Cement mortar + 240 mm red brick + 20 mm Mixed mortar” in the building simulation model. The wall thickness and heat transfer coefficient settings of the simulation model are shown in Table 1. The post-retrofit walls were referenced to the Design standard for energy efficiency of rural residential buildings [19]. Rural residents are in a poor indoor thermal environment for a long time, and the indoor temperature is usually around 16 °C [20]. Therefore, in this paper, the indoor air conditioning system is set to control the indoor air temperature at 16 °C to simulate the indoor heating situation, so that the simulation is closer to the actual condition. The heating season is from 15 November to 15 March, and the heated rooms include living room, bedrooms, study room and bathrooms. The input parameter of ventilation rates is 0.5 volumes/h with reference to the Design standard for energy efficiency of rural residential buildings [19]. The indoor heat disturbance value and the working hours of people, lights and equipment are set regarding the default value of DeST-h and the Standard for lighting design of buildings [21]. All input parameters are shown in Appendix A.

### Table 1. Heat transfer coefficient settings of the simulation model.

<table>
<thead>
<tr>
<th>Enclosure Structure</th>
<th>Thickness and Material of Each Layer from Outside to Inside</th>
<th>Heat Transfer Coefficient K (W/(m²·K))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exterior wall</td>
<td>Pre-retrofit: 20 mm Cement mortar + 240 mm red brick + 20 mm Mixed mortar</td>
<td>1.79</td>
</tr>
<tr>
<td></td>
<td>Post-retrofit: 20 mm Cement mortar + 240 mm red brick + 46 mm Polystyrene foam (EPS) + 20 mm Mixed mortar</td>
<td>0.65</td>
</tr>
<tr>
<td>Roof</td>
<td>20 mm Reinforced concrete + 43 mm Polystyrene foam (EPS) + 20 mm Cement mortar</td>
<td>0.50</td>
</tr>
<tr>
<td>Exterior window (south)</td>
<td>Hollow glass casement window (6 + 6A + 6)</td>
<td>2.80</td>
</tr>
<tr>
<td>Exterior window (others)</td>
<td>Hollow glass casement window (6 + 12A + 6)</td>
<td>2.50</td>
</tr>
<tr>
<td>Exterior doors</td>
<td>wooden exterior door</td>
<td>2.50</td>
</tr>
</tbody>
</table>

#### 2.4. Thermal Comfort Model

As argued above, PMV proposed by Professor Fanger (1970) is a more comprehensive index for evaluating indoor thermal comfort than air temperature [22]. It combines four environmental variables (i.e., air velocity, air temperature, mean radiant temperature and relative humidity) and two individual variables (metabolic rate and clothing) to reflect the thermal equilibrium relationship between the human body and the environment. However, people in an uncomfortable indoor environment will adapt to the environment through certain behavioral adjustments, so the adaptive thermal comfort (APMV) theory is more applicable to the rural buildings in this study. Equation (1) shows the assessment of APMV based on the PMV indicator.

$$\text{APMV} = \frac{\text{PMV}}{1 + \lambda \cdot \text{PMV}}$$ (1)

where $\lambda$ is the adaptive coefficient [23], when PMV $\geq 0$, $\lambda = 0.24$, and when PMV $< 0$, $\lambda = -0.50$.

In the sleep state, clothing resistance consists of bed, mattress, bedding, pillow and so on, which can no longer be selected according to ASHRAE Standard 55-2017. Therefore, Lin., et al. proposed Equation (2) to describe the PMV in sleeping condition termed SMPV [24].

$$\text{SPMV} = 0.0998 \left\{ 40 - \frac{1}{5} \left[ (34.6 - \frac{h_r + h_c}{h_r + h_c}) + 0.3762(5.52 - P_a) \right] \right\} - 0.0998[0.056(34 - t_a) - 0.692(5.87 - P_a)]$$ (2)
where $R_t$ is the total clothing resistance, clo; $h_r$ is the radiation heat transfer coefficient, $W/(m^2\cdot K)$; $h_c$ is convective heat transfer coefficient, $W/(m^2\cdot K)$; $T_r$ is the mean radiant temperature, °C; $t_a$ is the air temperature, °C; and $P_a$ is indoor air water vapor partial pressure, kPa.

2.5. Research Methods

The building envelope included exterior walls, roofs, doors and windows. The exterior walls accounted for the largest proportion of the rural building facade area, which has important influence on the building energy consumption and indoor thermal comfort. The object of this manuscript is to study and provide references for rural building exterior walls retrofitting, the heat transfer coefficient of exterior walls was thus set as an independent variable while ensuring that the heat transfer coefficients of other envelope structures remain unchanged. The paper takes the exterior wall envelope structure without adding insulation layer as “original building”, and the heat transfer coefficient of the envelope structure meets the requirement of heat transfer coefficient in Design standard for energy efficiency of rural residential buildings as the “standard building”.

In order to compare and analyze conveniently, single analysis was:

1. Calculate the APMV of each room and compare the effect of the envelope on the thermal comfort of the room at the same indoor air temperature;
2. Calculate the energy saving rate of buildings before and after retrofitting at the same thermal comfort value, and explore the impact of envelope energy retrofitting on building energy needs for space heating during the heating season;
3. Adjust the thickness of the insulation layer of the envelope to obtain the linear relationship between the indoor thermal comfort values and the heat transfer coefficient by adjusting the thickness of insulation layer with different heat transfer coefficients.

3. Results and Discussion

3.1. The Effect of Exterior Wall Envelope Insulation on Thermal Comfort

The hourly values of indoor air temperature, humidity and internal surface temperature for all rooms were obtained by simulations with DeST software, and the values from the simulations were imported into the CBE [25] thermal comfort calculation tool to obtain the hourly values of room PMV. The APMV under a typical meteorological year of the living room and study is calculated by Equation (1), as shown in Figures 2 and 3. Due to the large number of experimental simulation results, this paper presents the room thermal comfort in box-line diagram (5 days/box) for the heating season.

Figure 2 shows from 15 November to 30 November, the APMV mean values in the living room of the original and standard building were predicted to be $-0.86$ (with daily mean values from $-0.95$ to $-0.62$) and $-0.78$ (with daily mean values from $-0.86$ to $-0.52$). From 1 December to 28 February, with the outside temperature gradually decreased, the APMV values in both buildings decreased, the average APMV of the original building was maintained around $-0.87$ and the average APMV of the retrofitted regulated building was maintained at $-0.8$.

Figure 3 shows the modelled APMV for the study room, which more intuitively demonstrate the effect of building envelope retrofit on indoor thermal comfort. The modelled mean APMV for the original building study was $-0.9$ (with daily mean values from $-1.02$ to $-0.67$), the modelled mean APMV for the regulated building was $-0.76$ (with daily mean values from $-0.82$ to $-0.46$).

During the nighttime, the occupants in sleeping state were assumed to be 0.7 met and the 4.5 clo [26], respectively. The hourly values of indoor air temperature, humidity and inner surface temperature in the bedroom at night are obtained by DeST software, the SPMV values for the sleeping condition were calculated by Equation (2) and shown in Figures 4 and 5.
3. Results and Discussion

3.1. The Effect of Exterior Wall Envelope Insulation on Thermal Comfort

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Figure 2. PMV in the living room during heating season: (a) original building and (b) standard building.

Figure 3. PMV in the study room during heating season: (a) original building and (b) standard building.

During the nighttime, the occupants in sleeping state were assumed to be 0.7 met and the 4.5 clo [26], respectively. The hourly values of indoor air temperature, humidity and inner surface temperature in the bedroom at night are obtained by DeST software, the SPMV values for the sleeping condition were calculated by Equation (2) and shown in Figures 4 and 5.

Figure 4 shows the SPMV daily mean values of the original building’s south-facing bedroom varies from −0.04 to 1.17 with seasonal mean value of 0.42 during the heating season. While the SPMV daily mean values of the standard building south-facing bedroom varies from 0.47 to 1.07, and the seasonal mean value during the heating season is 0.63.
Figure 4. SPMV in the heating season for south-facing bedrooms: (a) original building and (b) standard building.

Figure 5 shows the SPMV daily mean values of the original building’s north-facing bedroom varies from $-0.09$ to $0.95$ with seasonal mean value of $0.34$ during the heating season. While the SPMV daily mean values of the standard building south-facing bedroom varies from $0.47$ to $1.07$, and the seasonal mean value during the heating season is $0.63$, which has the same trend and similar values as the south-facing bedroom.

In this part, we simulated the APMV of the original building and the standard building with the envelope insulation retrofit at the same indoor temperature, and compares the simulation results. The simulation results show that even though the indoor air temperature
reaches the thermal expectation temperature of indoor residents, the indoor APMV is still at a low level, indicating that the indoor temperature is not an important indicator of indoor thermal comfort. Additionally, this result is consistent with the field survey, in which the residents thought that the indoor temperature had been adjusted to a high level, but the indoor cold feeling was obvious.

At the same time, it was found that the reason for the large difference in room APMV at the same temperature was the internal surface temperature. In winter, the outdoor air temperature is always lower than the indoor temperature, so the heat in the room is conducted through the walls, and even though the room is maintained at a neutral temperature by heating equipment, the temperature of the inner surface of the original building is still low, which increase the radiative heat loss of human bodies. The hourly inner surface temperatures of the original and standard building during the heating season from the DeST software simulation, are shown in Figure 6 (taking the living room and south-facing bedroom as an example).

![Figure 6. The dynamically inner surface temperature: (a) living room and (b) south facing bedroom.](image)

### 3.2. The Energy Saving Rate Based on Thermal Comfort

To obtain the indoor thermal comfort requirements of a building, two methods are often used: (1) passive methods, which is to narrow the gap between outdoor climate and indoor thermal comfort through the building itself, such as increasing envelope insulation measures; and (2) active methods, which is to regulate through environmental equipment, such as raising the heating temperature. After several simulation cases, the paper obtained that after increasing the indoor air temperature of the original building model by 1.5 °C, the APMV value of original building could be close to that of the standard building. Therefore, this paper calculates the heat load, respectively, with these two different methods when achieving the same APMV, taking the original building with an indoor air temperature of 16 °C as a reference, and the results are shown in Figure 7.

The results show that the energy saving rate of the standard building with the addition of the envelope insulation under the same indoor air temperature was 67%, and the cumulative heat load was increased 13% by raising the indoor air temperature of the original building to achieve the same indoor thermal comfort level. Raising the indoor temperature, on the one hand will increase the indoor APMV, and on the other hand will make the accumulated heat load during the heating season increase, which is not promoted from the perspective of energy saving. The temperature difference between indoor and outdoor increases makes the energy needs for space heating of the building increase, and the energy saving rate of the regulated building can reach 71% under the same thermal comfort.
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Figure 7. Cumulative heat load in heating season.

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### 3.3. The Relationship between the Indoor Thermal Comfort Values and the Heat Transfer Coefficient

In order to make the APMV index better applicable to the retrofit of rural buildings, this study calculates the indoor thermal comfort values under different heat transfer coefficients and analyzes the data to find out the correlation between the envelope heat transfer coefficient and indoor thermal comfort under the same air temperature. The study modified the thickness of the thermal insulation material from 0 mm to 50 mm with step of 10 mm, and repeat the APMV simulation. Table 2 shows the heat transfer coefficient of the envelope and the mean APMV values at different insulation thicknesses. Figure 8 shows the negative correlation between human indoor thermal comfort and the heat transfer coefficient of the enclosure.

Table 2. The heat transfer coefficient of the envelope and the mean APMV values at different insulation thicknesses.

<table>
<thead>
<tr>
<th>Thickness of the Thermal Insulation Material (mm)</th>
<th>Heat Transfer Coefficient K (W/(m²·K))</th>
<th>Mean APMV Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1.30</td>
<td>−0.86</td>
</tr>
<tr>
<td>20</td>
<td>1.02</td>
<td>−0.85</td>
</tr>
<tr>
<td>30</td>
<td>0.84</td>
<td>−0.84</td>
</tr>
<tr>
<td>40</td>
<td>0.71</td>
<td>−0.80</td>
</tr>
<tr>
<td>50</td>
<td>0.62</td>
<td>−0.76</td>
</tr>
</tbody>
</table>

The results show that the heat transfer coefficient of the envelope structure and the indoor thermal comfort value are monotonically decreasing, which means that the higher the heat transfer coefficient, the higher the indoor APMV value. However, the thermal comfort is not as good as the higher value, but in the range of 0 to −0.5 is more suitable for indoor human body. Therefore, it can be concluded that it is more appropriate to maintain the heat transfer coefficient at 0.5 W/(m²·K).
indoor and outdoor increases makes the energy needs for space heating of the building promoted from the perspective of energy saving. The temperature difference between make the accumulated heat load during the heating season increase, which is not temperature, on the one hand will increase the indoor APMV, and on the other hand will original building to achieve the same indoor thermal comfort level. Raising the indoor

Figure 8. Relationship between indoor thermal comfort and heat transfer coefficient.

4. Conclusions

This study mainly focuses on rural residential buildings and establishes a typical building energy efficiency retrofit model based on field investigations. Through theoretical simulations, the thermal comfort and energy performance of the rural buildings with improved insulation are analyzed. There are three main conclusions obtained from the simulations in the article.

(1) Setting the building model parameters to control the original building and the specification building are at the same indoor air temperature. The APMV of the original building is always lower than the standard building, indicating that the indoor temperature is not representative of the thermal comfort of the room.

(2) Adding a building envelope can reduce the cumulative heat load while enhancing indoor thermal comfort. Compared with the original building with the same thermal comfort value, the energy saving rate after adding envelope insulation is 67%.

(3) By adjusting the thickness of the insulation layer, the paper obtains the relationship between the heat transfer coefficient and the indoor APMV value. Additionally, according to this equation, the heat transfer coefficient of the envelope should not be higher than 0.5 W/(m²·K) when the room is in comfort.

The meteorological parameters in this paper are based on a typical meteorological year rather than a specific year; the indoor temperature is based on a survey of thermal expectation temperatures from previous literature; and the practices of the envelope are based on the actual data, so this study has certain references for the retrofitting of rural buildings in north China.

Author Contributions: J.N. conceptualized the study to evaluate rural building retrofits with thermal comfort, developed the research method, supervised the co-authors and edited the manuscript. Y.P. did the formal analysis, investigation and wrote the original draft. H.Z. did data curation, validation and visualization work. C.W. did the funding acquisition, visualization and review-editing work. K.Y. provided building information resources, validated the paper and supervised the research team. All authors have read and agreed to the published version of the manuscript.

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Informed Consent Statement: Not applicable.
Data Availability Statement: The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

The dynamically meteorological input parameters of the building model are shown in Figure A1 and Table A1.

**Figure A1.** Meteorological parameters of the Beijing area.

**Table A1.** Input parameters of the building model.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Outdoor Air Temperature (°C)</th>
<th>Heat Transfer Coefficient</th>
<th>Indoor Air Temperature (°C)</th>
<th>Relative Humidity (%)</th>
<th>Ventilation Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inputs</td>
<td>Dynamically meteorological of DeST</td>
<td>Pre-retrofit: 1.79 Post-retrofit: 0.65</td>
<td>Winter: 16 °C Summer: 25 °C</td>
<td>Winter: 30% Summer: 60%</td>
<td>1 time per 2 h</td>
</tr>
</tbody>
</table>

The model input with indoor heating change with time are shown in Tables A2–A5.

**Table A2.** Parameter setting of room thermal disturbance.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Bedroom</td>
<td>6</td>
<td>0</td>
<td>53</td>
<td>0.061</td>
<td>3</td>
</tr>
<tr>
<td>The study</td>
<td>6</td>
<td>9.3</td>
<td>53</td>
<td>0.061</td>
<td>3</td>
</tr>
<tr>
<td>Living room</td>
<td>6</td>
<td>9.3</td>
<td>53</td>
<td>0.061</td>
<td>3</td>
</tr>
<tr>
<td>Bathroom</td>
<td>6</td>
<td>0</td>
<td>60</td>
<td>0.102</td>
<td>1</td>
</tr>
<tr>
<td>Stairwell</td>
<td>7</td>
<td>6</td>
<td>53</td>
<td>0.061</td>
<td>3</td>
</tr>
</tbody>
</table>
Table A3. The application rate of lights, equipment and personnel of bedroom and study at different times.

| Rate/Time | 0     | 1     | 2     | 3     | 4     | 5     | 6     | 7     | 8     | 9     | 10    | 11    | 12    | 13    | 14    | 15    | 16    | 17    | 18    | 19    | 20    | 21    | 22    | 23    |
|-----------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Lights    | 0%    |       |       |       |       |       |       |       | 50%   |       | 100%  |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
| Equipment | 0%    |       |       |       |       |       |       |       | 50%   |       | 100%  |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
| Personnel (Weekdays) | 100%  |       | 0%    |       | 50%   |       | 100%  |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
| Personnel (Weekends) | 0%    |       | 33.3% |       | 100%  |       | 33.3% |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |

Table A4. The application rate of lights, equipment and personnel of living room at different times.

| Rate/Time | 0     | 1     | 2     | 3     | 4     | 5     | 6     | 7     | 8     | 9     | 10    | 11    | 12    | 13    | 14    | 15    | 16    | 17    | 18    | 19    | 20    | 21    | 22    | 23    |
|-----------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Lights    | 0%    |       |       |       |       |       |       |       | 100%  |       | 50%   |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
| Equipment | 0%    |       |       | 68.8% |       | 0%    |       | 100%  |       | 0%    |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
| Personnel (Weekdays) | 0%    |       | 33.3% |       | 0%    |       | 33.3% |       |       |       |       | 100%  |       | 0%    |       |       |       |       |       |       |       |       |       |       |       |
| Personnel (Weekends) | 0%    |       | 33.3% |       | 100%  |       | 0%    |       |       |       |       | 33.3% |       | 100%  |       |       |       |       |       |       |       |       |       |       |

Table A5. The inputs for PMV and SPMV calculation.

<table>
<thead>
<tr>
<th></th>
<th>Air Temperature (°C)</th>
<th>Relative Humidity (%)</th>
<th>Inner Surface Temperature (°C)</th>
<th>Air Velocity (m/s)</th>
<th>Metabolic Rate (met)</th>
<th>Clothing Level (clo)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMV</td>
<td>Derived from DeST report</td>
<td>Derived from DeST report</td>
<td>Derived from DeST report</td>
<td>0.15</td>
<td>1.2</td>
<td>1.0</td>
</tr>
<tr>
<td>SPMV</td>
<td>Derived from DeST report</td>
<td>Derived from DeST report</td>
<td>Derived from DeST report</td>
<td>0.15</td>
<td>0.7</td>
<td>4.5</td>
</tr>
</tbody>
</table>

References


20. Shao, T.; Jin, H. A field investigation on the winter thermal comfort of residents in rural houses at different latitudes of northeast severe cold regions, China. *J. Build. Eng.* 2020, 32, 101476. [CrossRef]


