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# Improvement of Human Comfort in Rural Cave Dwellings via Sunrooms in Cold Regions of China

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**Abstract:** Economic development limits the living quality of rural residents. In particular, the residential buildings in northern China generally have poor thermal comfort in winter, which affects the physical and mental health of residents. Because of the separation of rooms, residents who live in cave dwellings often have to enter and leave rooms in the course of their daily lives, which leads to worse thermal feelings in winter. Because of the low price and the wind insulation and heat storage, sunrooms are widely used in renovations of rural houses. The traditional purpose of the addition of a sunroom is to provide a buffer room between outdoor and indoor spaces. This manuscript focuses on improving the degree of thermal comfort by means of a sunroom connecting all rooms. This study selected two families with the same number of members and similar daily activities as the study cases. One of the families had a sunroom built to connect its bedroom, living room, and washroom. The household's air temperature and human comfort were measured both on holidays and on workdays. It is demonstrated that adding a sunroom can significantly stabilize the thermal environment and increase the air temperature in both the bedroom and the living room. Adding a sunroom can increase the air temperature of a cave dwelling's main room by 1.0 °C on workdays and 4.3 °C on holidays. A cave dwelling with a sunroom can also provide residents with a decent level of human comfort for 24.4% of their daily time on workdays and 39.1% of the time during holidays. This research demonstrates that a sunroom can not only increase the air temperature in cave dwellings but also enhance the stability of human comfort. The conclusion provides new renovation ideas for improving the living comfort of cave dwellings.

**Keywords:** rural revitalization; cave dwelling; sunroom; air temperature; human comfort; thermal stability

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## 1. Introduction

Earth-covered architecture makes up a significant proportion of traditional Chinese rural dwellings. In the northern part of China's Loess Plateau, cave dwellings, as a typical traditional architectural form, have been widely and extensively used for a long time. Initially, cave dwellings were mainly adopted in rural areas due to their minimal requirements for additional construction materials and their strong thermal stability. Particularly in cold regions of northern China, cave dwellings have been regarded as representative examples of "warm in winter and cool in summer" passive buildings and have been extensively used [1,2].

Since 1992, China's overall economic strength has been developing rapidly, and people's demand for comfortable living conditions has gradually increased. In 2018, the Chinese government officially proposed the strategy of rural revitalization. However, compared to the development of rural economies, living environment conditions still lag behind, and the indoor living thermal environment of traditional cave dwellings can no longer meet the current residents' demands for quality of life [3].

The negative impact of low indoor temperatures or drastic temperature changes on residents' physical and mental health has attracted the attention of researchers. Numerous medical studies have confirmed that living in cold rooms may lead to a range of adverse health consequences, including respiratory problems [4–6], cardiovascular diseases [7], mental disorders, social isolation, and an increased risk of falls [8]. The UK Health Security Agency recommends a minimum indoor temperature of 18 °C [9]. The World Health Organization also recommends a minimum indoor temperature of 18 °C under normal circumstances [10]. In 2002, China also established national standards, considering a heating standard of 16–20 °C for indoor temperatures during winter. This standard can be regarded as the recommended indoor temperature for winter in China [11].

However, due to the early construction times of rural residential buildings and their relatively inferior quality compared to urban buildings, it is usually challenging to achieve the recommended indoor temperature standards in rural areas. Some scholars argue against directly applying urban living environment evaluation models to rural areas [12,13]. It should be noted that the imbalanced development between urban and rural areas restricts rural families from using more energy to improve indoor temperatures, and it is not feasible to demolish and rebuild residential buildings in the short term. This necessitates architectural scholars to face the current conflict between the characteristics of rural economies and the demand for thermal comfort and to select suitable methods for building renovation in rural areas.

### *1.1. Research Scope and Data Collection*

Research on cave dwellings is generally categorized as research on earth-sheltered architecture. Zhou summarized it as "the need for more reasonable functional layout in indoor space, the need to improve the indoor thermal and physical environment due to poor ventilation, humid summer, and low indoor temperature in winter" [14].

In recent years, local case studies in Asia have received much attention from scholars in response to these issues [15–17]. Because there are a large number of earth-sheltered architectural buildings in the inland areas of China, Chinese authors account for a relatively large proportion of this research. Although the research mainly focuses on Asia, it still includes various climate regions, such as subtropical grasslands [18,19], tropical monsoon areas [20], dry hot–cold areas [21], and so on. In addition, Europe also accounts for a large amount of research on the thermal environment of earth-sheltered architecture [22–24].

Among these studies, there are both quantitative studies (on-site monitoring, simulation models) and qualitative studies (questionnaire surveys) [19,21]. Among them, the combination of on-site short-term monitoring and questionnaire-based resident surveys is widely adopted by scholars [17,18,25]. When conducting on-site monitoring, air temperature and relative humidity are the factors of greatest concern [26,27], followed by wind speed and surface temperature [28,29]. Among these, air temperature and relative humidity are usually measured together, but some scholars have only conducted research on air temperature [23].

The outdoor environmental parameters monitored on site have received slightly less attention compared to indoor environmental parameters, and more scholars regard them as the same data as regional meteorological parameters. The outdoor parameters mainly concern air temperature, relative humidity, and wind speed [29,30], and some scholars have also paid attention to solar radiation and weather conditions [27]. Although scholars have attempted to select the most recent and suitable data files for research, the most recent typical meteorological stations may sometimes be located 80 or 90 km away [29,30]. This situation emphasizes the importance of on-site outdoor data collection. Because on-site measurements often have incomplete data types, Mohammadi, Timur, Juan, and others adopted a combination of outdoor data from on-site measurements and meteorological station data [31–33].

### *1.2. Renovation of Rural Earth-Sheltered Architectural Thermal Environments*

There have been numerous studies conducted internationally focusing on the rural living environment or the thermal environment of earth-covered architecture. For example, Wang studied the correlation between indoor thermal environments and human comfort in urban and rural residences in extremely cold regions and proposed indicators such as the average thermal sensation and indoor operating temperature [34]. With the increasing attention of scholars paid to rural living environments, a large amount of research has been conducted on the indoor and outdoor thermal environments in cold regions of China. Lv investigated specific improvement measures for rural habitat construction from the perspective of sustainable rural development [35]. By using computational simulations, Peng compared the thermal environment characteristics before and after different renovation methods for rural dwellings and proposed renovation measures for optimizing the thermal environment [36]. By studying the glass color of residential buildings and the opening mode of curtains, the influence of architectural forms on thermal load was analyzed [37]. Zhang used the Probit method to explore the expected thermal sensation of farmers and herdsmen in winter indoor environments [38].

In addition, some scholars have explored the impact of geographical environment, climate, and living space on human living conditions. Irena discussed the influence of meteorological conditions on rural life, particularly how changes in weather conditions affect residents' health [39]. Schorr conducted surveys on the social activities of the elderly in urban and rural areas to identify their needs regarding living environments [40].

Whether from the perspective of architecture or environmental studies, it has been noted that scientific active and passive building technologies can improve the thermal environment of earth-sheltered architecture.

### *1.3. Building Technology Aimed at Improving Thermal Environments*

Scholars have conducted studies on the impact of rural architecture or regional traditional building techniques on the comfort of residential buildings [41]. In these studies, many scholars recognize the adaptability and feasibility of passive design techniques in rural housing construction [42]. Nadarajan compares the thermal environment of rural houses with different wall materials without auxiliary heating equipment through computational fluid dynamics (CFD) simulations [43]. Similar research includes Manoj's study on the thermal environment of old rural residential buildings [12] and Aimilios's study on how to enhance natural ventilation to improve nighttime indoor environments in rural constructions [44].

With the deepening research on building structures and material performance by scholars, Albatici discovered that passive solar energy utilization techniques, whether obtained indirectly or directly, can reduce energy consumption while maintaining a comfortable living environment. They are particularly suitable for the renovation of existing buildings [45]. The addition of a sunroom can improve the indoor environment without generating additional carbon emissions, making it highly suitable for promotion in the current global low-carbon development context. The low cost, fast construction speed, and minimal impact on the stability of the original building structure have made sunrooms popular among rural residents [46].

It should be noted that there are many passive solar energy technologies, such as double-layered walls [47], solar collectors [48], Trombe walls [49], solar chimneys [50], and so on. Although these technologies have attracted attention from scholars and architectural companies, their inability to adapt to rural residential renovation and construction is primarily due to issues related to price and their impact on building forms.

In the study of the correlation between the addition of sunrooms and the thermal environment of residential buildings, Aelenei used EnergyPlus to study the performance of solar spaces in Portugal and found that sunrooms can reduce heating demand by 48% in winter [51]. Chen combined the characteristics of traditional rural courtyards in China and set up sunrooms externally in traditional residential buildings. Through calculations, it was found that courtyards with sunrooms have an average winter temperature that is 4.3 °C higher than that of the original courtyards, resulting in a 34.2% reduction in heating energy consumption [52,53].

The aforementioned studies focused on the building itself and explored the compatibility of sunrooms with rural residences. However, the fundamental purpose of researching thermal environment and thermal comfort is to enhance human living environments. Therefore, research focusing on human behavior and activity habits is currently needed as a supplement. Residents do not spend their entire day in a single room or house; they move between indoor and outdoor areas or different areas within the same building for work, dining, bathing, and other activities. This is particularly true for traditional segmented dwellings like cave dwellings, where residents need to move through outdoor areas to access different rooms due to changes in their daily activities. Therefore, studying the influence of sunrooms on residents' thermal comfort requires focusing on their activity habits.

This study quantitatively investigates the influence of adding sunrooms on the thermal comfort of residents in cave dwellings in cold regions of China under similar living behaviors and activity habits. By comparing the different daily routines and holiday and weekday behavioral changes in male and female hosts in two households, this study explores the living thermal comfort of the residents. Ultimately, the feasibility and effectiveness of adding sunrooms to improve the winter thermal environment of cave dwellings are confirmed. This research's findings provide practitioners in the construction industry with a better understanding of the potential improvements that sunrooms can bring to cave dwellings, and exploratory research on thermal comfort in daily continuous activities is carried out.

## 2. Research Methods

### 2.1. Research Framework

This study included four stages: research case selection, data collection, indicator selection and calculation, and examination of the impact of sunrooms on human comfort (as shown in Figure 1). The first step (blue part in the figure) was to select two households that were willing to participate in this study and that have similar living environments. After that, we built a sunroom in the cave dwelling of one household. Then, we collected thermal environment data and lifestyle behavior data for the two households separately (green part in the figure). Next, we calculated the environmental temperature and human comfort indicators separately, where the environmental temperature is obtained from the thermal environment data in the second step, and the human comfort indicators are calculated from the thermal environment data and living behavior data (orange part in the picture). Finally, a comparative study was conducted on the impact of sunroom on the environmental temperature of cave dwellings and the human comfort of residents (red part in the picture).

### 2.2. Research Site

This research selected Mafang Village in Nanniwan Town, Yan'an City, as the research site. The location is at 36.3 degrees north latitude and 109.7 degrees east longitude, and the terrain is a typical loess plateau hilly and gully area, with an average elevation of 1230 m. The climate is characterized by variable temperatures, large temperature differences, and distinct seasons. The average annual temperature is 8.1 °C, with the lowest average temperature being 2.2 °C in January and February and the highest average temperature being 29.7 °C in July and August. Because the site is located in a rural area without industrial and mining enterprises nearby, and there is no urban heat island effect, the perceived temperature in winter is lower than the actual temperature.

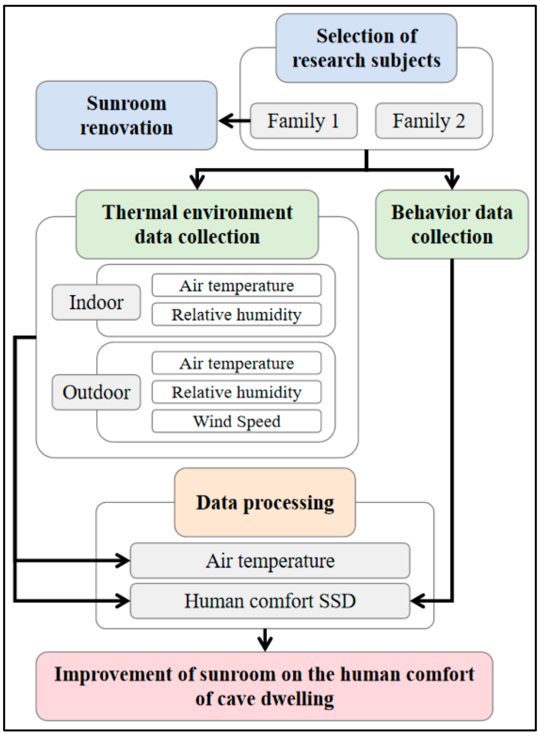


**Figure 1.** Flow diagram of this research.

Due to the climatic characteristics of Mafang Village, a large number of cave dwellings are used as daily residential buildings. Because cave dwellings use thick layers of soil as enclosing structures, they have good thermal insulation properties. The interior of a cave dwelling is usually believed to have the temperature characteristics of "warm in winter and cool in summer." However, with economic development and people's increasing requirements for living environments, the traditional notion of a "comfortable" living environment can no longer meet people's demand for thermal comfort in residences. In order to understand the actual indoor thermal environment characteristics of cave dwellings, this study conducted field measurements and research at Mafang Village as the research site.

### *2.3. Measurement Methods*

#### 2.3.1. Selection of Representative Measurement Periods

Due to the significant heating demand in Yan'an City during winter and the absence of cooling demand in summer, this study focused on conducting field measurements during the winter season. The measurement period was from 31 January 2022 to 21 March 2022, covering the coldest months of winter. Specifically, 1 February 2022 marked the first day of the Chinese Spring Festival, and 20 March 2022 represented the traditional Chinese festival known as the "Spring Equinox," which symbolizes the end of winter. The measurement started one day in advance to ensure the preheating of the instruments and ended one day later to ensure the completeness of the data for the final day.

It should be noted that this selected period was chosen to reflect two different living conditions during the Chinese winter. This is mainly because the Chinese Lunar New Year is the most important traditional festival in China. During this holiday period, almost all Chinese people choose to celebrate with their families, typically lasting for 7 to 14 days. This period is a statutory holiday in China, and therefore, regardless of whether individuals usually live with their families or not, Chinese people usually stay together as a family unit during this time.

Due to this characteristic, there are two completely different living patterns for families during the winter season. One is the regular daily living pattern, and the other is the holiday pattern. In the manuscript, we use capitalized words "WORKDAY" and "HOLIDAY" to refer to these two types of life periods.

In the WORKDAY living pattern, there are fewer residents living inside the cave dwellings, usually elderly family members. As the elderly have generally frugal habits, they usually live in a single cave dwelling and reduce the number of times they enter and exit other cave dwellings to minimize the loss of indoor temperatures. The period from 15 February to 28 February (2 weeks) was selected as a representative time period. In the HOLIDAY pattern, the number of residents significantly increases due to the gathering of family members who work elsewhere. To accommodate the concentration of people, there is a significant amount of interaction between multiple cave dwellings. The period from 1 February to 14 February (2 weeks) was selected as a representative time period of HOLIDAY.

The traditional Spring Festival is the most important holiday in China, with the 31st of January to the 6th of February being the official holiday in China. In rural areas, because there is no clear work schedule, villagers usually regard the period between Chinese New Year's Eve (31 January 2022) and Lantern Festival (15 February 2022) as the holiday. To ensure equal duration, we chose both 2-week measurement periods for the HOLIDAY (31 January–14 February 2022) and WORKDAY (15–28 February 2022) patterns; the data after the 28th of February were not used in this study.

It should be noted that the daily activities of urban residents during the measurement period were greatly affected by the COVID-19 pandemic. However, the study area for this research is located in relatively remote rural areas, where the impact of the pandemic on daily life can be neglected.

#### 2.3.2. Measurement Equipment and Measuring Points

The measuring equipment and measuring points are shown in Figure 1. The experiment utilized Onset HOBO MX2301A as the measurement equipment to record the air temperature and relative humidity. The air temperature measurement range of this device is −40 to 70 °C, with an accuracy of ±0.25 °C (−40 to 0 °C) and ±0.2 °C (0 to 70 °C). The relative humidity measurement range is 0% to 100% RH, with an accuracy of ±2.5%. To avoid direct sunlight, a shading cover made of aluminum foil was used to cover the equipment.

To measure the influence of sunrooms on human living comfort, we selected two adjacent families for this study. The status of these two families is similar; the number and size of each family's cave dwellings are also the same. We built a sunroom (light blue part in Figure 2) for the west-side residents (family 1), while the building for the east-side residents (family 2) remained unchanged.

We selected two adjacent households for measurement, and a total of 12 measurement points were set up. There were 7 measurement points set up in the room of Family 1 (with a sunroom), and 4 measurement points set up in the room of Family 2. Measuring point 0 was located on the courtyard wall and used to measure the outdoor temperature and humidity. Measuring points 1 and 1′ were located in the bedroom of Family 1, measuring points 2 and 2′ were located in the living room of Family 1, measuring points 3 and 3′ were located in the sunroom of Family 1, and measuring point 4 was in the restroom. Correspondingly, measuring points a and a′ were located in the bedroom of Family 2, and measuring points b and b′ were located in the living room of Family 2. When measuring the bedroom and living room, two measurement points were set at the center and against the wall of the room. For the measurement of the sunroom, measurement points were set on the east and west sides of the sunroom, respectively. It should be pointed out that in order to avoid the impact of residents' daily activities on the measurement results, the equipment was placed in a location that was not easily accessible to people within a range of 1.2 to 2 m from the ground.

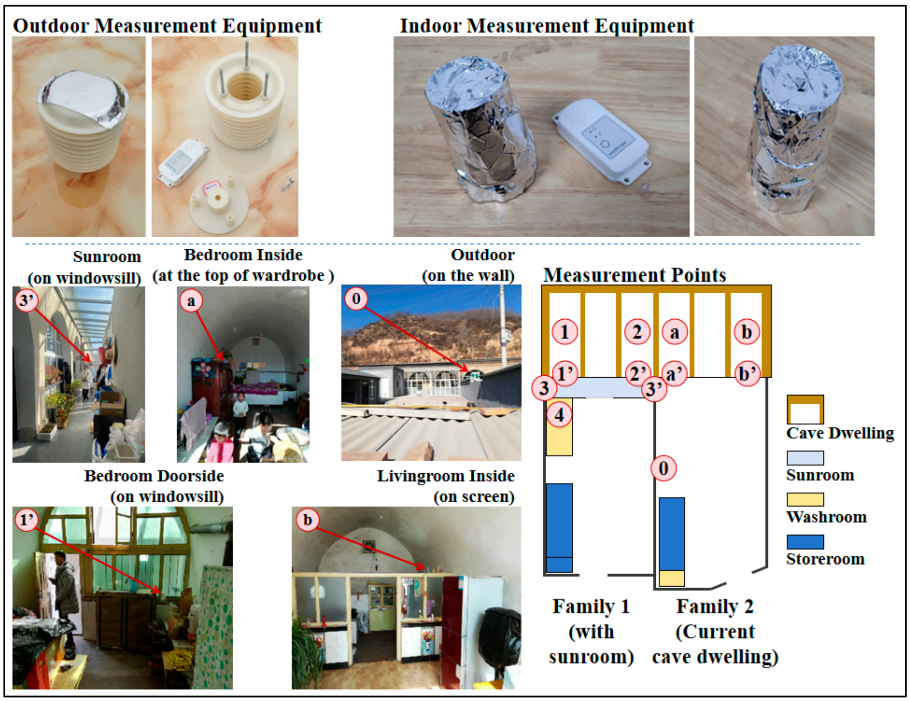


**Figure 2.** Diagram of measurement equipment and placement locations.

### 2.3.3. Data Processing

Due to the unique characteristics of the cave dwelling space, every time the door is opened or closed, there is a temperature exchange between the indoor and outdoor environments. However, the duration of this phenomenon is relatively short. Therefore, in this study, temperature and humidity data were collected every 5 s. In indoor measurement, human activities that are close to the equipment would have an impact on temperature and humidity. To avoid outliers caused by human activities, the data were averaged every hour. Since each room had measurement points near the door and in the center of the room, the temperatures at these two points were also averaged, which better represented the overall thermal environment of the cave dwelling.

In addition, to comprehensively consider the impact of temperature and humidity on human thermal comfort, this study also adopted the human comfort index SSD provided by the China Meteorological Administration for evaluation. Human comfort SSD comes from the Roman pronunciation of the first letter of the Chinese word "comfort degree". The SSD index considers the air temperature, humidity, and wind speed. The classification of SSD levels follows the unified standards specified by the China Meteorological Administration, using a nine-level classification method, as shown in Table 1. To distinguish between general descriptions of thermal perception and SSD levels, in this manuscript, SSD level descriptions are in uppercase letters.

**Table 1.** Grade of Human Comfort Index SSD in China.

| SSD | Level | Human Comfort Level, Perception |
|---|---|---|
| >85 | Level 4 | VERY HOT, impaired heat regulation, extremely uncomfortable. |
| 81–85 | Level 3 | HOT, very uncomfortable, prone to excessive sweating. |
| 76–80 | Level 2 | WARM, uncomfortable, prone to sweating. |
| 71–75 | Level 1 | SLIGHTLY WARM, moderately comfortable, slight sweating. |
| 61–70 | Level 0 | COMFORTABLE, most acceptable to people. |
| 51–60 | Level −1 | SLIGHTLY COOL, relatively comfortable. |
| 41–50 | Level −2 | COOL, uncomfortable. |
| 20–40 | Level −3 | COLD, very uncomfortable, slight decrease in body temperature. |
| <20 | Level −4 | VERT COLD, extremely uncomfortable, shivering. |

Currently, SSD is used by meteorological stations in China for calculating comfort levels. The formula used in this study is the calculation formula for the SSD index used by meteorological stations in Shandong Province, which has been widely applied in northern China.

$$SSD = (1.818t + 18.18)(0.88 + 0.002f) + (t - 32)/(45 - t) - 3.2v + 18.2$$

Here, SSD is the human comfort index, t is the air temperature, f is the relative humidity, and v is the wind speed. Among them, SSD is a dimensionless quantity, with air temperature in "°C", relative humidity in "%", and wind speed in "m/s".

In this study, the indoor environment was assumed to have no wind during measurements, and the outdoor wind speed data were obtained from the Yan'an Meteorological Station.

## 3. Sunroom Construction Methods and Residents' Behavioral Characteristics

### 3.1. Description of Sunroom Construction Plan

Figure 3 shows the typical form of an "independent cave dwelling" in the traditional Chinese cave-dwelling residential style. This type of cave dwelling is commonly found in rural areas of the mountainous regions in northern Shaanxi province, China. The main features of this type of architecture include the following: only one side of the room allows for natural lighting, the roof of the building has a thinner layer of soil compared to other cave-dwelling forms, and the depth of the building is slightly greater than that of cliff-side cave dwellings. These architectural characteristics give rise to unique living thermal environments in independent cave dwellings.

**Figure 3.** Typical form of independent cave dwelling.

Firstly, the limited natural lighting due to only one side of the building receiving sunlight results in less solar radiation received during winter, which is unfavorable for natural indoor heating. Secondly, the thinner soil covering on the roof compared to other forms of cave dwellings results in weaker insulation performance. Considering that there is no need for summer heat insulation in the northern Shaanxi province, this feature usually affects the winter heating demand of the cave dwelling. Furthermore, because each room in a cave dwelling-style building is not interconnected, residents must pass through outdoor spaces when engaging in different activities.

To address the aforementioned issues, our team proposed a renovation method of adding a sunroom on the exterior of the cave walls to connect all cave entrances. The effectiveness of the sunroom in improving the insulation performance of traditional cave dwellings has been confirmed by scholars. Our team hopes to optimize the thermal environment of residents' lives through this renovation method, which minimally impacts the original architectural form. The specific renovation plan is shown in Figure 4. To confirm the feasibility of this renovation method, we selected another household adjacent to the renovated building as a control group. The two households have the same population composition and similar daily activity behaviors; the result can effectively demonstrate the impact of sunrooms on the winter living thermal environment.

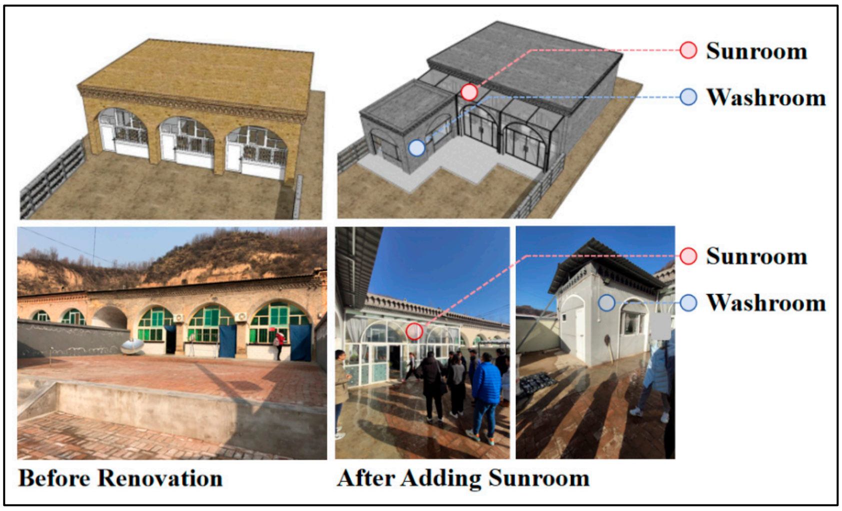


**Figure 4.** Comparison of sunroom addition plan and the images before/after renovation.

*3.2. Residents' Behavioral Characteristics*

Figure 5 shows the daily life behaviors of the two households involved in this research. The horizontal axis in the figure represents "family number–resident gender", and the color blocks represent the spaces where the residents are located at the corresponding time. Blue represents the bedroom space, yellow represents the living space, green represents the bathroom, and red represents the outdoor space.

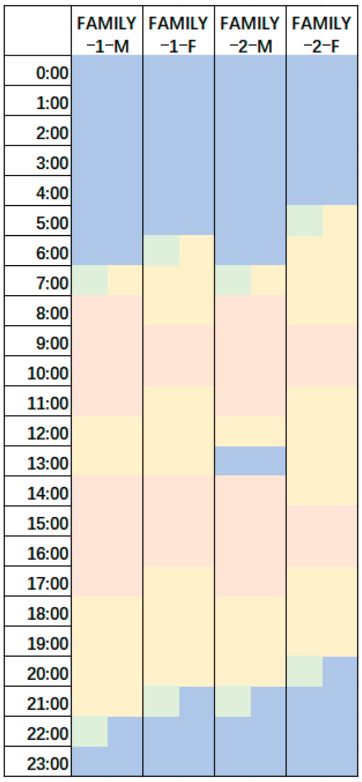


**Figure 5.** Resident living timelines.

Unlike urban residents, rural residents have a more consistent daily rhythm. Residents typically wake up around 6 a.m. and go to bed around 9 p.m. Usually, they go to the bathroom after getting up and before going to sleep. It should be noted that Interviewee 2-F mentioned that the timing of bathroom visits is not always the same. For example, on snowy days, they do not immediately go to the bathroom to wash up after waking up. Instead, they wait until after finishing breakfast at around 7 a.m. This is because the weather around 5 a.m. is too cold, and the ground may be icy, making it not only uncomfortable but also potentially dangerous to go outside to the bathroom before sunrise. Only Interviewee 2-M takes a nap at noon, while the others typically rest or engage in activities in the living room or courtyard after lunch. Additionally, Interviewee 1-M works for the local government, while the other three primarily work in agriculture. As this study was conducted during the winter season when agricultural work is less intensive, the other residents' periods of going out were generally similar.

Based on these living flow lines, this paper not only studies the thermal environment of a single space but expands the research on the SSD all-day change characteristics of each resident.

## 4. Renovated Living Thermal Environment Characteristics

### *4.1. Impact of Sunroom Renovation on Indoor Thermal Environment in Cave Dwellings*

#### 4.1.1. Bedroom (Main Activity Space)

(1) Air Temperature

Figure 6 shows the temperature variations in the main activity room during the HOLIDAY. The blue line represents the outdoor temperature changes during this period, with a maximum of 22.1 °C, a minimum of −10.5 °C, and an average temperature of 3.6 °C. The orange and gray curves represent the average indoor temperatures of the cave dwellings with and without the addition of a sunroom, respectively. It can be observed that there is a noticeable difference between the two cases before 7 February. The hourly average temperature in the main activity room with the added sunroom is increased by 4.3 °C, allowing the indoor temperature in Case 1 to be maintained at around 15.2 °C, with a minimum daily temperature of 11.8 °C. However, the average temperature of the main activity room in Case 2 (without sunroom) can only reach 13.1 °C, with a minimum temperature of 7.7 °C.

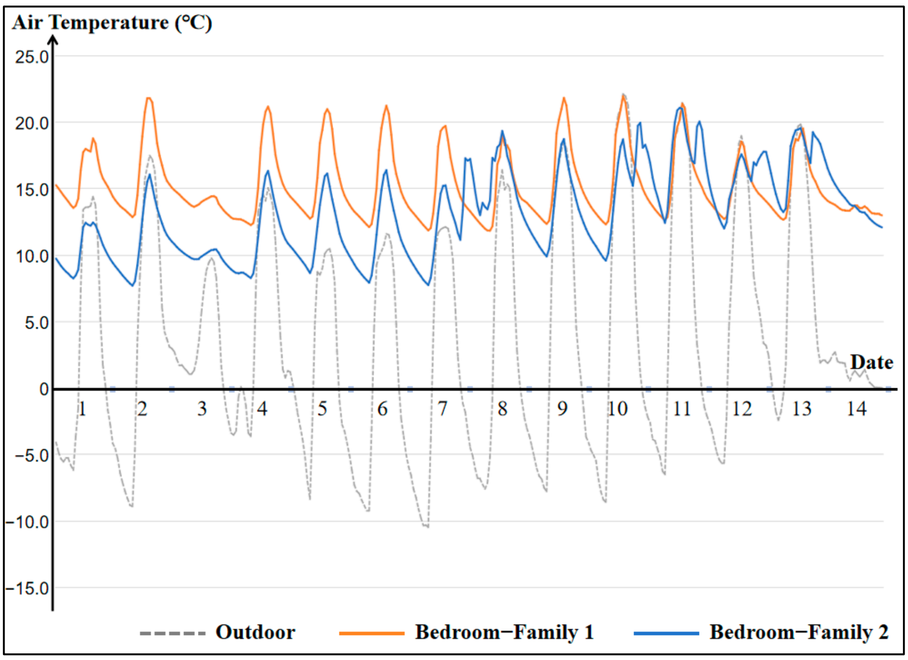


**Figure 6.** Bedroom air temperature during HOLIDAY.

From 8th to 14th February, there is no difference in the average temperature between the two cases. It should be noted that although the average temperature remains the same, the peak temperature (in the afternoon) in Case 1 is still significantly higher than that in Case 2. However, in Case 2, there is a noticeable increase in temperature every evening (starting around 19:00) from 7 February and during the 6 days from 10th to 14th February, resulting in higher nighttime temperatures compared to Case 1. The reason for these temperature characteristics is that relatives visited and stayed in Case 2 from 7 February until the end of the holiday period, including a baby. In order to avoid excessively low indoor temperatures at night, Case 2 used a coal stove to heat the room every evening. This led to a distinct "double peak" trend in the indoor temperature of Case 2 starting from 7 February.

In addition, in both cases, since the children of the households were living there during the holiday period, both families used coal stoves for heating indoors after getting up in the morning and stopped heating immediately after going out for activities between 8 a.m. and 9 a.m. This heating pattern resulted in higher indoor temperatures in Case 1 during the first 7 days of the holiday compared to Case 2 and the outdoor temperature.

Figure 7 shows the temperature variations in the main activity room during the WORKDAY. Within this time period, Case 1 exhibits an hourly average temperature that is 1.0 °C higher than Case 2. The main difference between the two cases occurs from sunrise to sunrise of the next day, during the period of temperature rise (from sunrise to noon), where the temperature difference between the two cases is relatively small. This difference becomes more pronounced on days with larger outdoor temperature variations (19–13 February and 27 February).

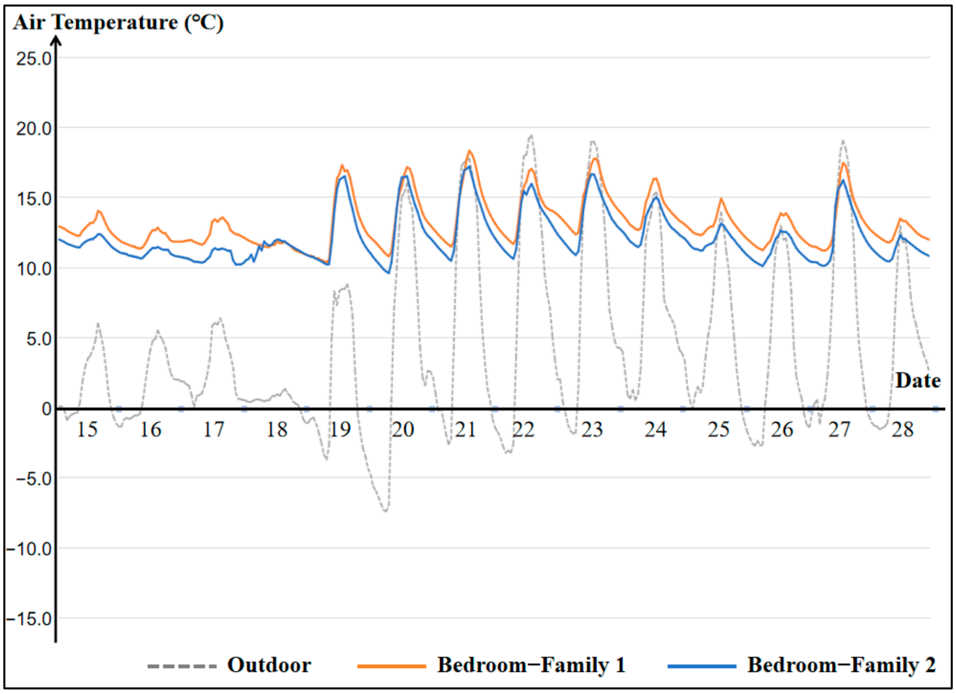


**Figure 7.** Bedroom air temperature during WORKDAY.

The primary reason for this variation is that, after the end of the Spring Festival, the children in both households return to their workday residence (in the city). As a result, both households reduce the use of coal stoves for heating. Since there is a lack of artificial heat sources, the impact of a sunroom, usually made of glass, on indoor air temperature due to solar radiation is minimal. This leads to smaller temperature differences between the two cases during the temperature rise stage. However, as solar radiation decreases, the ability of the sunroom to block long-wave radiation becomes increasingly evident, resulting in a noticeable increase in temperature for Case 1 compared to Case 2 during the temperature decrease stage.

Furthermore, by comparing the temperature variations during HOLIDAY and WORKDAY, it can be observed that due to reduced artificial heating behavior by residents after the holidays, the indoor temperature range decreases from 11.8 to 21.9 °C (Case 1) and 7.7 to 21.1 °C (Case 2) during the HOLIDAY to 10.4 to 18.3 °C (Case 1) and 9.6 to 17.2 °C (Case 2) on WORKDAY. Additionally, during the holiday period, the hourly average temperature in Case 1 is 4.3 °C higher than in Case 2, which decreases to 1.0 °C after the reduction in artificial heating. Although the temperature difference between cases significantly decreases with the reduction in the use of artificial heating, the presence of a sunroom still contributes to an increase in indoor temperature in the main activity spaces.

(2) Human Comfort SSD

Figure 8 shows the distribution characteristics of thermal comfort SSD in the main activity spaces during HOLIDAY and WORKDAY. It can be observed that the presence of sunlight contributes to an increase in SSD, regardless of the use of artificial heating.

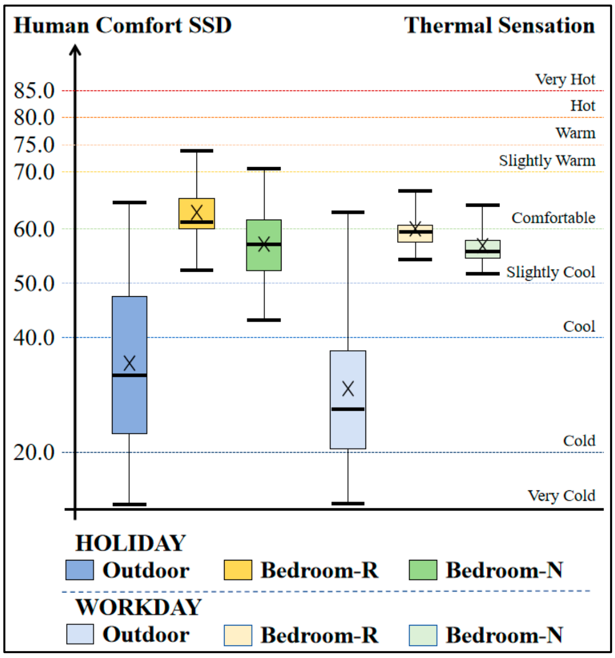


**Figure 8.** Bedroom human comfort.

During the HOLIDAY, due to the use of artificial heating, there is a noticeable increase in the maximum value, minimum value, and the second and fourth quartiles of SSD in the main living spaces. The maximum value of SSD increases by 2.8, the minimum value increases by 9.3, and the average value and median increase by 5.5 and 4.3, respectively. In terms of thermal sensation, after the addition of a sunroom, there are no longer periods of feeling COOL or colder. The average value and median of SSD are closer to the comfortable range.

During the WORKDAY, there is also a certain improvement in the maximum value, minimum value, and the second and fourth quartiles of SSD in the main living spaces compared to rooms without sunrooms. The aforementioned four indicators increase by 3.0, 2.8, 3.1, and 3.0, respectively. The magnitude of this change is not as significant as during the HOLIDAY, but after the construction of a sunroom, there are some periods in which the thermal sensation falls within the comfortable range between the second and fourth quartiles, accounting for 24.4% of the regular day period.

4.1.2. Living Room (Secondary Activity Space)

(1) Air Temperature

Due to the single spatial form of the cave dwelling, usually, only one or two types of activity occur in a single cave. The secondary activity cave mainly functions as a living room, and the activities in this cave are mainly dining and cooking. It should be noted that the living conditions of rural residents in Yan'an are poorer than those in cities. Agricultural work takes up a lot of time, so leisure and entertainment activities have a shorter duration. These activities, such as watching TV or playing cards, mainly take place in the primary activity space.

Figure 9 describes the air temperature characteristics of the cave dwelling used for secondary activities during HOLIDAY.

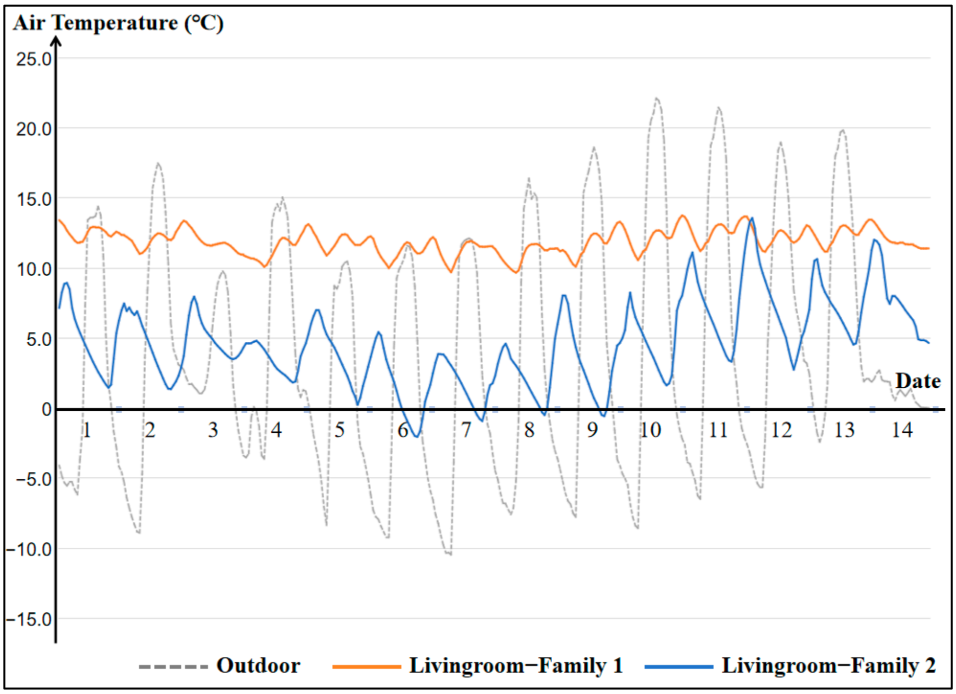


**Figure 9.** Living room air temperature during HOLIDAY.

The orange and gray curves in the figure represent the temperature changes in the secondary activity spaces of Family 1 and Family 2, respectively. The trend reflects the different living behaviors of the two families. Because the husband of Family 1 works in the village government and has a lifestyle similar to that in urban life, there is a characteristic of three meals a day. Therefore, the orange curve is noticeably more stable, with two distinct peaks occurring around noon (around 12:00) and dinner time (around 19:00). On the other hand, both the husband and wife of Family 2 engage in agricultural work. They only cook once in the morning and reheat the food for lunch and dinner without cooking again. As a result, the temperature in their home rises noticeably in the morning and gradually decreases afterward.

In addition to the differences in the temperature curve caused by cooking activities, Room 1, which has a sunroom extension and additional heat generated twice a day due to cooking, has a significantly higher temperature than Room 2. The highest temperature, lowest temperature, and average temperature in the living room of Family 1 are 13.7 °C, 11.9 °C, and 9.6 °C, respectively. On the other hand, Family 2 has a similar highest temperature of 13.6 °C, but this feature only exists from 11th February to 14th February. The average temperature in the secondary activity space of Family 2 is 4.6 °C, while the average outdoor temperature during the same period is 3.6 °C.

In addition to the differences in temperature curves caused by cooking activities, Case 1, which has a sunroom extension and additional heat generated twice a day due to cooking, has a significantly higher temperature than Case 2. The highest temperature, lowest temperature, and average temperature in the living room of Family 1 are 13.7 °C, 11.9 °C, and 9.6 °C, respectively. On the other hand, Family 2 has a similar highest temperature of 13.6 °C, but this feature only exists from 11th February to 14th February. The average temperature in the secondary activity space of Family 2 is 4.6 °C, while the average outdoor temperature during the same period is 3.6 °C. The difference between indoor and outdoor is only 1 °C. Therefore, although man-made heat can quickly increase the temperature in the cave dwelling, the addition of a sunroom can provide a more stable and warmer indoor temperature throughout the day. This feature can also be observed from the temperature variations in the two measured rooms. The temperature differences and interquartile ranges (IQRs) of the cave dwellings for Family 1 and Family 2 are 1.0 °C and 4.1 °C, and 4.1 °C and 15.7 °C, respectively. The value for Family 2 is significantly larger than that for Family 1. For indoor temperature, a larger temperature difference indicates poorer thermal comfort (poor thermal stability).

As shown in Figure 10, due to the functional characteristics of cave dwellings, the secondary living spaces are used for cooking and dining. These activities do not show significant differences between holidays and workdays. Therefore, the temperature variation trends in the secondary living spaces during WORKDAY are similar to those during HOLIDAY, with only slight decreases due to the decrease in outdoor temperature.

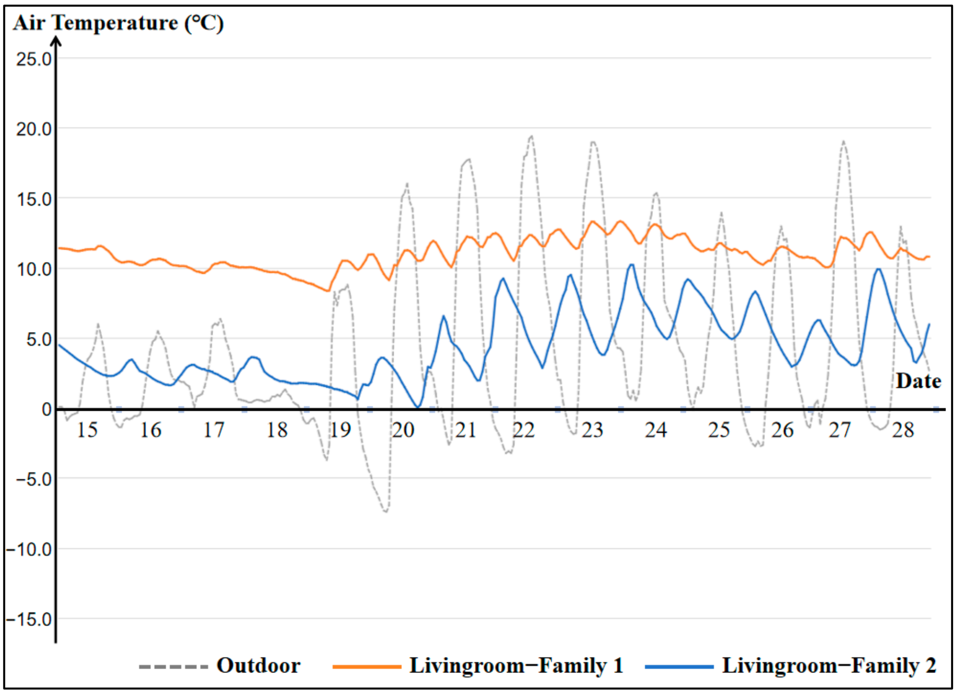


**Figure 10.** Living room air temperature during WORKDAY.

(2) Human Comfort SSD

Figure 11 describes the distribution of thermal comfort SSD in secondary activity spaces during holidays and regular days. Like in primary activity spaces, the addition of a sunroom results in an overall increase in temperature and a decrease in temperature difference in secondary activity spaces.

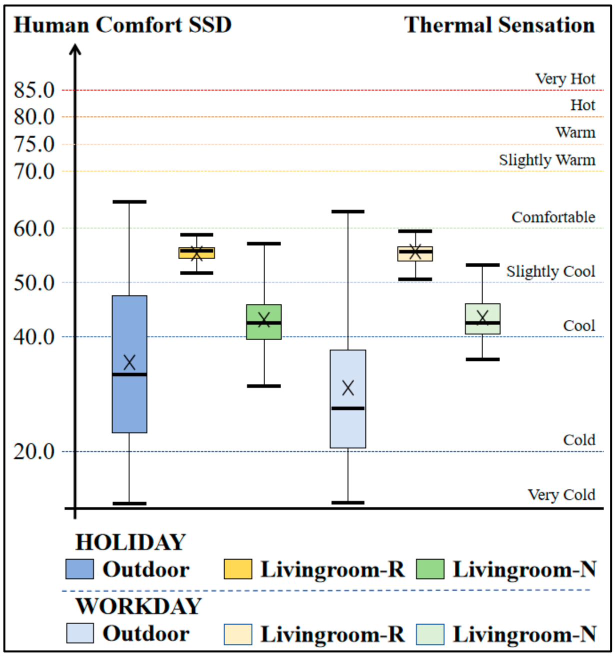


**Figure 11.** Living room human comfort.

During holidays, the indoor maximum and minimum and the IQR of SSD in the secondary activity space with a sunroom are 58.8, 52.0, and 1.8, respectively. The corresponding SSD values of traditional cave dwellings in secondary activity spaces are 57.0, 31.4, and 7.2. This indicates that the addition of a sunroom can reduce the SSD difference by 18.8 and narrow the IQR of the SSD index by 5.4. The overall improvement in SSD, especially the increase in the lowest SSD value, can significantly enhance the thermal sensation in winter. The smaller SSD difference also indicates a constant thermal comfort in the room.

The effect of adding a sunroom on SSD in secondary activity spaces during WORKDAY is similar to that during HOLIDAY. It can increase the maximum and minimum SSD values by 6.1 and 14.8, respectively, and reduce the SSD daily difference and IQR by 8.7 and 3.6, respectively.

In terms of thermal sensation, the addition of a sunroom can maintain a SLIGHTLY COOL sensation in secondary living spaces throughout the day. For rural indoor environments in winter, this thermal comfort level can meet residents' expectations. Overall, the addition of a sunroom can maintain a SLIGHTLY COOL thermal sensation in the cave dwelling's indoor environment for 99.6% of the time. However, the thermal sensation of traditional cave dwellings' secondary living spaces mainly falls within the COOL range, with only 6.8% of the time falling in the SLIGHTLY COOL range.

#### 4.1.3. Sunroom

(1) Air Temperature

Numerous scholars have already studied the correlation between the sunroom temperature and the outdoor temperature. The measurements conducted by our team confirmed some of the existing research conclusions. In Figure 12, the measurement results indicate that the temperature inside the sunroom is generally higher than the outdoor temperature, with a maximum daily temperature increase of 16.3 °C. After sunrise, the temperature inside the sunroom increases at a similar rate to the outdoor temperature. In the afternoon, when the outdoor temperature begins to drop, the rate of temperature decrease inside the sunroom slows down noticeably. This change in temperature characteristics is due to the sunroom heat storage capacity and indoor heat generation.

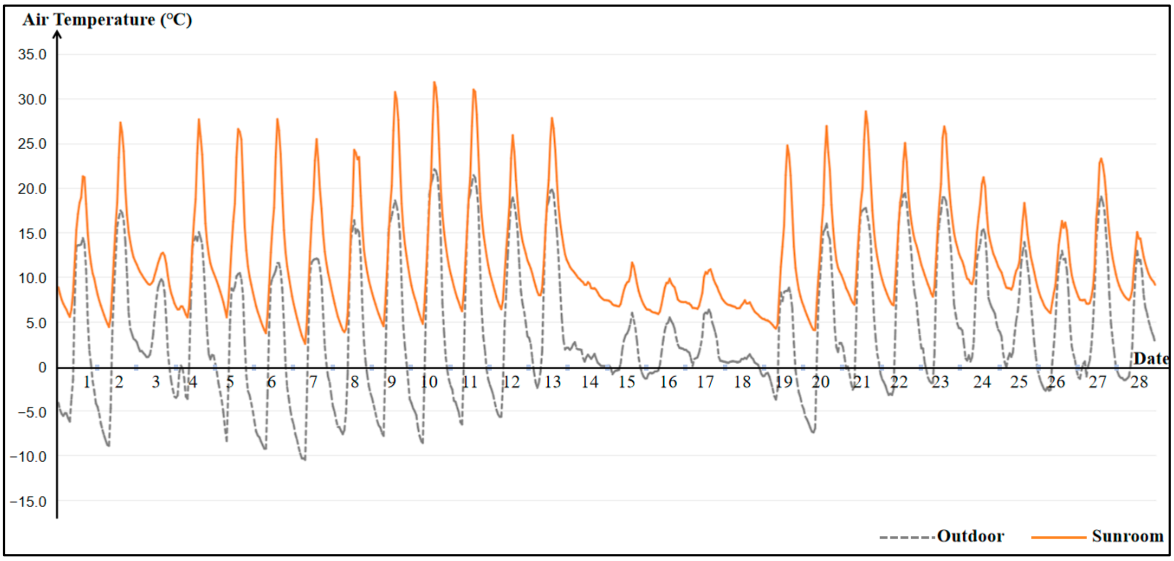


**Figure 12.** Sunroom air temperature.

(2) Human Comfort SSD

Since the sunroom primarily serves as an indoor passageway in cave dwellings and people usually spend a short time inside it, studying the thermal comfort of the sunroom alone has limited significance. However, the results obtained from this measurement demonstrate a significant improvement in thermal comfort inside the sunroom compared to the outdoors. As shown in Figure 13, in the sunroom, 38.2% of the daily time period falls within the "SLIGHTLY COOL" range of thermal sensation, 14.4% falls within the "COMFORTABLE" range, and 10.6% falls within the "SLIGHTLY WARM" or hotter range. In contrast, outdoors, only 11.6% and 3.4% of the time falls within the "SLIGHTLY COOL" and "COMFORTABLE" ranges, respectively, with no "SLIGHTLY COOL" or warmer periods observed.

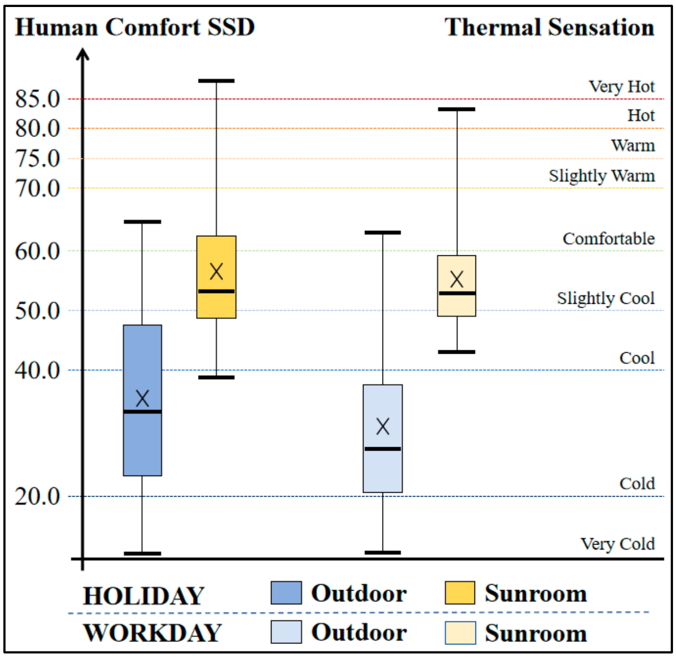


**Figure 13.** Sunroom human comfort.

*4.2. The Impact of Sunroom Construction on Human Comfort in Daily Activity*

Section 4.1 analyzed the temperature and SSD changes in different spaces after adding a sunroom. This section compares the changes in human comfort in daily living for two households (as clarified in Section 3.2).

Figure 13 shows the human comfort changes in the whole day for four villagers, with different colors representing each person's living space. The two blue lines and the yellow lines have similar changing trends, with their maximum and minimum values being almost identical. As shown in Figure 14, the minimum SSD index values for the four residents are 19.1 (household 1—male), 20.2 (household 1—female), 18.6 (household 2—male), and 20.2 (household 2—female). According to the definition of SSD, when the SSD value is below 21, it means that a very cold thermal environment has occurred. It should be noted that these minimum values appear for a short time and mainly occur when the villagers go out to work (outdoors). The maximum SSDs for the four residents are 65.5, 65.5, 70.5, and 69.4, respectively. Although the maximum value for household 2 is higher than that for household 1, this is mainly due to the increased heating caused by additional guests, particularly children, during the night festival period, as explained in Section 4.1.

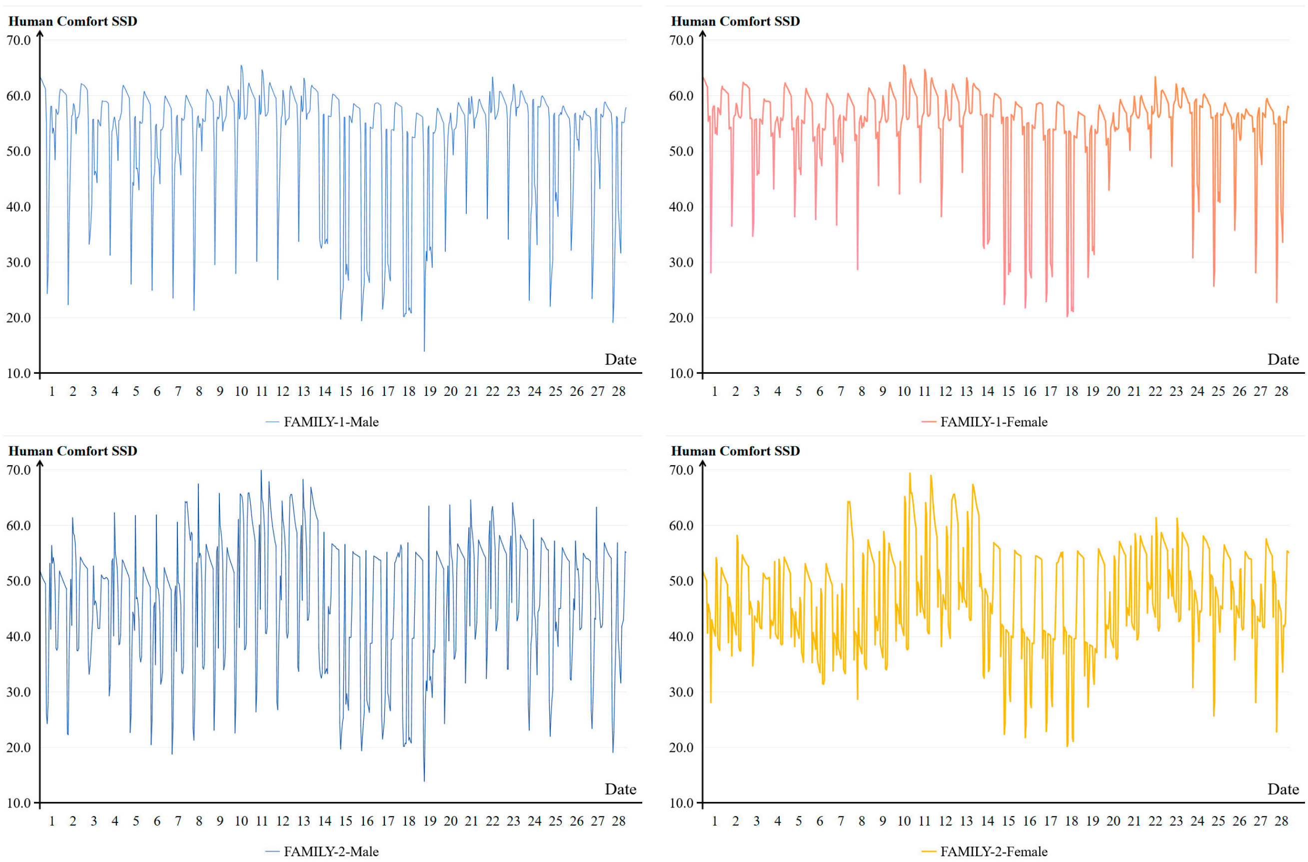


**Figure 14.** SSD value of four residents' daily activity.

The most significant difference between the two families is the valley value of SSD. There are two obvious valleys and two weaker valleys in the SSD of both residents of household 1. The behavior causing obvious valley SSD values appears during the morning and afternoon work periods, while the weaker two valleys appear in the early morning and when villagers go to the bathroom at night. Household 2 also has four valleys in SSD values every day, except for two work periods; going to the bathroom at night significantly reduces the SSD values.

Furthermore, according to Figure 15, the existence of the sunroom leads to a significant difference in the SSD changes for the two households. Due to the changes in solar radiation and the two outdoor activities every day, the maximum and minimum SSD values of the two households are relatively small. However, there is a significant difference in the interquartile range between household 1 (average SSD interquartile range of 5.6) and household 2 (average SSD interquartile range of 15), with a difference of 9.4. According to the definition of SSD, when the human comfort level is below COMFORTABLE, the SSD value difference for each level is 10. When the interquartile range reaches 9.4, we can conclude that the thermal comfort of the daily living space for household 1 is one level higher than that for household 2.

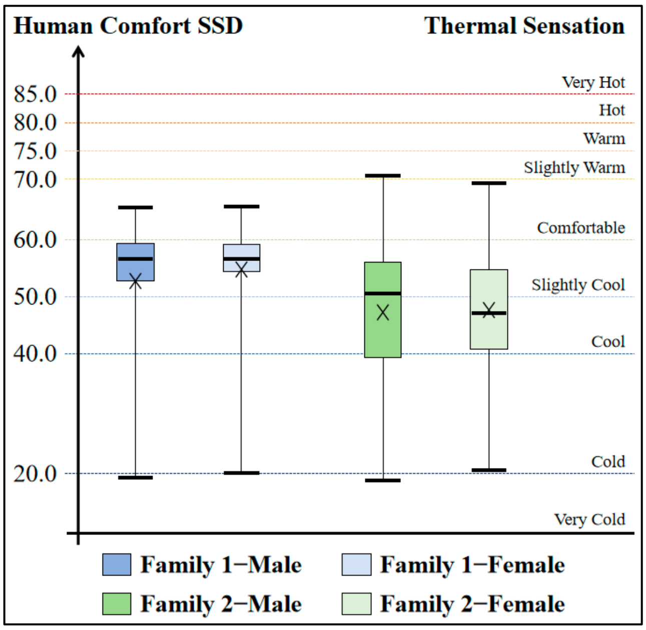


**Figure 15.** Human comfort for different residents.

## 5. Discussion

### *5.1. Methods and Contents of Rural Residential Building Renovation in Northern Shaanxi*

Since China proposed the rural revitalization strategy, Shaanxi Province put forward more region-specific "Work Points for Rural Habitat Environment Improvement" in 2019. The policy includes several articles specifically supporting the renovation of rural housing environments, such as ". . . creating. . . livable demonstration rural houses with local flavors, economical costs and green environmental protection." Under this supportive policy, scholars have focused on new rural residential renovation technologies that take into account climate characteristics, regional features, and functional needs. The core goal of renovating rural houses in northern China is to improve winter indoor thermal comfort without increasing the economic pressure on rural households.

Among them, the sunroom has once again attracted a great deal of attention from scholars due to its simple construction technology, wide material sources, and low cost. Unlike scholars' focus on the heat transfer characteristics of sunrooms in the 1990s, this article hopes to study how to use sunrooms to improve overall living comfort through actual measurement research. This study differs from existing research by focusing more on the practical economic development status and real-life behavior patterns of traditional cave dwellings rather than just new forms of cave dwellings. We obtained affordable renovation options and cave-dwelling living behavior characteristics through field measurement research.

Therefore, we selected two families with similar cave dwelling styles, family compositions, and living behaviors and studied the daily changes in residents' human comfort levels based on their behavior. The measurement results prove that sunrooms not only have the ability to improve the thermal environment inside the cave dwelling but also provide a buffer space linking other living spaces, avoiding the need for traditional cave dwellings to have different rooms connected by outdoor spaces.

The technology of sunrooms is not new, but this article provides a new renovation idea for the focus on sunrooms by changing the concept that they are mainly used for windproofing and warmth to instead improve the thermal environment coherence of related functional spaces.

### *5.2. Economical Comparison of Different Renovation Methods for Improving Thermal Comfort of Cave Dwellings*

Thermal conductivity, density, specific heat, and heat transfer rate are the parameters of greatest concern when discussing the thermal performance of materials and enclosure structures [54]. Some studies have also focused on material thickness, transmittance, and the cold air permeability coefficient concerning doors and windows. Due to the thermal characteristics of the overlying soil layer in cave dwellings, this research focuses more on optimizing the material thermal parameters at the entrance of the cave dwellings [31,55].

This feature provides various methods for the thermal environment renovation of cave dwellings. Due to the thermal characteristics of the overlying soil layer in cave dwellings, we focus more on the renovation of the entrance to the cave dwellings. Some scholars have conducted research on design parameters such as door and window selection, sunlight room width, etc., as these parameters have a significant impact on the cost of renovation. Using Energyplus software (https://energyplus.net/), Zhang calculated that a suitable setting for a sunroom can increase the average indoor temperature by 2.38 °C in winter. This conclusion is consistent with the fact that a sunroom can increase the average indoor temperature by up to 5.0 °C, as measured in this article [56].

Similar studies have also appeared in the selection of glass windows; Oliveti proposed that the effective absorption coefficient of a sunroom is between 0.54 and 0.62 [57]. Hilliaho and Mottard also reached similar conclusions [58,59]. Unlike the consistent research conclusions of scholars on glass absorption, there are significant differences in the research conclusions on the width of construction between sunrooms. Ulpiani believes that a sunroom with a depth of 1500 mm is the most energy-efficient [60]. However, Zhang believes that this value should be 600 mm [56]. Li proposed from the perspective of architectural function that the most suitable depth for a sunroom should be above 1200 mm [61].

As proposed in this article, when carrying out building renovations in rural areas, we cannot simply discuss their improvement capabilities, as price factors are sometimes more important. We compared the thermal insulation performance of renovating cave doors and windows with the construction cost of adding a sunroom (neither renovation method requires changing the cave structure, and the renovation technology is relatively easy). We estimate the thermal conductivity of the doors and windows of traditional cave dwellings to be 3.5 and 5.8 $W/(m^2{\cdot}K)$, respectively. In traditional renovations, optimizing the insulation performance of doors and windows by replacing low-e glass, the thermal conductivity of glass windows can be optimized to 1.6 $W/(m^2{\cdot}K)$, and doors can be made of 5 cm, 2 $W/(m^2{\cdot}K)$ materials. When completing the renovation of the sunroom, the depth of the sunroom was set to 1500 mm, and the aforementioned low-e glass was still selected. Based on market prices, it is estimated that the renovation of traditional door and window materials would cost approximately 7400 (windows) + 3600 (doors) = CNY 11000, and adding a sunroom would cost approximately CNY 20500. By simulating the winter energy performance of different renovation methods using Energyplus software and assuming coal-fired boilers as indoor heating equipment, we found that adding a sunroom will save about 0.60 tons of coal per year while optimizing door and window materials will save 0.34 tons of coal. Based on an estimated price of CNY 1300 per ton of anthracite, the investment return period for optimizing door and window materials is about 24.8 years, while that for a sunroom is about 26.3 years. Without considering structural aging, the investment return period difference between the two renovation methods is relatively small. However, it should be pointed out that the above statistics do not include the fact that sunrooms can be used to connect houses, avoiding the thermal environment changes that residents may experience when going from one room to another. Overall, adding a sunroom is a good renovation method from both the thermal comfort and economic perspectives.

### 5.3. The Fairness of Urban and Rural Residential Building Renovation

Compared with the renovation focus on old residential buildings or residential communities in urban renewal, rural residential buildings have different weather, regional, and economic backgrounds. When renovating urban and rural residential buildings, we cannot simply categorize “residential buildings built in cities” and “residential buildings built in rural areas.”

Regarding the low-carbon development direction of buildings (the research direction of this article), the core problem of urban buildings is their high energy consumption and energy waste. However, due to the extensive application of building technologies, such as air conditioning systems, the thermal comfort of urban residential buildings can be maintained within a relatively comfortable range. Therefore, the renovation of urban residential buildings can focus more on energy allocation, environmentally friendly materials, three-dimensional greening forms, and so on.

However, current rural residential buildings in China cannot provide stable and comfortable thermal environments for residents, and simply improving the thermal environment of the building itself, such as cave dwellings, cannot solve the fundamental problem of the rural population’s living thermal environment. Improving the thermal comfort of various living scenarios is the “shortest board” that can most effectively enhance rural residents’ living quality.

In addition, the differences in urban and rural economic development must also be considered by building designers. For example, the most common method used in China’s urban residential building renovation, adding external wall insulation boards, is not suitable for rural buildings. The reason why external wall insulation boards can be added to urban residential buildings is that there is a good cooling and heating system inside the buildings, and the enclosing structure only needs to partition the indoor space as much as possible and reduce heat exchange. However, due to economic constraints, rural residential buildings do not have independent and complete cooling and heating systems in every room. Especially for living forms like cave dwellings, where each room is not connected, many rural families cannot afford the one-time investment of setting up independent air conditioning systems for each room, as is done in urban residential buildings. As architecture researchers, we should not simply view this phenomenon as a problem of regional economic imbalances but should face the realistic living characteristics and urgent needs of rural families and carry out more practical research.

At the same time, fairness is also an issue that needs to be emphasized when carrying out urban and rural renewal and renovation in the future. The Chinese government has proposed two targeted supportive policies for urban and rural areas, namely, the “urban renewal strategy” and the “rural revitalization strategy.” Both policies involve the optimization of residents’ living environments. The use of renovation and optimization, rather than simply the “demolition–reconstruction” model, represents that the core principle is the redistribution of resources, and whether the distribution is reasonable requires a discussion of issues such as spatial justice and social equity. How to define the concepts of rights and fairness in the “redistribution” of living resources and evaluate the fairness between cities and rural areas and between different rural areas in a classified and graded manner, and construct a multi-level fairness analysis and evaluation framework is an urgent issue to be addressed in the future. It is clear that research on the renovation of rural living environments requires not only the participation of scholars in architecture design and technology but also the joint participation of other professional researchers in sociology, behavior science, law, and other fields.

### 5.4. Limitations

This study focused on investigating the role of sunrooms in improving the thermal stability of cave dwellings during winter. Although this study takes into account the differences in behaviors between holidays and workdays, the sample size is relatively small, and there are still some differences in the lifestyles of the two households. In future research, a larger sample size can be used to obtain more precise quantitative conclusions.

Furthermore, the sunroom renovation proposed in this study mainly applies to independent cave dwellings in the northwest and central provinces of China. The conclusions obtained can only serve as a qualitative reference for other "separate-unit" residential buildings (such as Chinese courtyard houses). Targeted research is still needed to assess the effectiveness of sunroom renovations for other types of buildings.

## 6. Conclusions

As a representative traditional dwelling type in cold regions of northern China, cave dwellings have been widely used in rural areas due to their insulation properties. With the overall improvement in China's economic strength, the original winter insulation performance of cave dwellings can no longer meet the current thermal comfort needs of rural residents. However, the lack of connected spaces between different functional areas in cave dwellings and the separation of kitchen and living spaces will continue to exist for a considerable period of time due to the architectural form of cave dwellings and the current economic development status of rural areas. This results in significant fluctuations in daily human comfort for residents, which seriously affects their physical and mental health.

As a representative passive solar energy application approach, China's sunroom construction technology has become quite advanced, with good timeliness and cost-effectiveness in terms of materials and construction. Sunrooms, as an important means of rapidly improving the thermal environment of cave dwellings, have gradually attracted attention from the construction industry once more.

This manuscript is different from the existing research that mainly focuses on the thermal environment characteristics of spaces. We adopted a comparative measurement method to study the improvement effect of connecting the various functional spaces of cave dwellings on residents' hourly human comfort variations. Considering the differences in behavior during holidays and workdays, we separately investigated these two time periods.

This research's findings are as follows:

Adding a sunroom can increase the hourly temperature of the main activity room by 4.3 °C (holidays) and 1.0 °C (workdays), resulting in average daily temperatures of 15.3 °C (holidays) and 13.2 °C (workdays). During holidays, the average temperature is close to the recommended standard of 16 °C for Chinese urban dwellings. Adding a sunroom can significantly stabilize the thermal environment of secondary activity rooms, reducing the temperature difference throughout the day and the interquartile range by 3.1 °C and 11.6 °C, respectively.

Adding a sunroom can significantly reduce the interquartile range of residents' daily Human Comfort SSD. The SSD for families with a sunroom has an average interquartile range that is 9.4 units smaller than that of those without a sunroom, and the thermal sensation level is improved by one level, both in terms of daily average and during the main activity period.

Sunrooms can bring the main activity space to a COMFORTABLE thermal sensation level for 24.4% of the time on workdays and even as much as 39.1% of the time during holidays. Sunrooms can also keep the secondary activity space within the SLIGHTLY COOL range for 99.6% of the time. In contrast, traditional cave dwellings only achieve this thermal sensation level for 6.8% of the time in the secondary activity space.

These results will help to optimize the existing renovation concepts, which only focus on the windproofing and insulation functions of sunrooms, and provide new ideas for improving human comfort stability in cave dwellings.

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