Case Study on Prefabricated Sunspace-Addition Renovation for Existing High-Rise Residential Buildings and Its Energy Consumption Simulations

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Abstract. A large number of existing high-rise residential buildings in China have problems such as high energy consumption and poor comfort. Renovating them is an important way for sustainable urban development. This article first introduces a European sunspace addition method for existing high-rise residences, and then sets up unit models of different depths for energy consumption simulation. Four cities of cold regions of China are selected and simulation comparison of original state, conventional renovation, sunspace addition and its variants are made. The size of the window, the presence or absence of external shading, and the presence or absence of internal curtains influence factors for the energy performance of the sunspace. In addition, the effects of changing depth of sunspace on winter heating energy consumption and summer cooling energy consumption, as well as the impact of different construction details on energy consumption were also studied. The article verifies the feasibility of the objective renovation mode in terms of energy consumption and summarizes the corresponding conclusions.

1. Introduction

Large number of high-rise residential buildings were built in China from the 1980s to 1990s, because the concept of energy conservation and environmental protection had not yet been popularized and constrained by economic conditions, less thermal insulation materials were used on external envelopes, which lead to high energy consumption. And it was to solve the problem of housing shortage, so house area size was relatively small, which cannot meet current user’s needs for domestic function and comfort; and after years of weathering, damage to the exterior wall is a common phenomenon.

Similar problems also exist in European countries. Over 70% of European existing buildings were built during the economic boom between the 1950s and 1970s. At that time, there were no specific regulations on building’s energy consumption, resulting in poor thermal performance and high fuel consumption [1]. However, some outstanding renovation examples have been achieved. One method is to add prefabricated sunspace unit outside existing buildings, as shown in the following three cases.

2. Case Studies

2.1. Bois-le-Prêtre Tower

Built in 1962, Bois-le-Prêtre tower is located on the edge of the city ring road in Paris. It has 16 floors and a height of 50 meters, with 4 to 8 units per floor. From 2005 to 2011, Lacaton & Vassal architects
collaborated with Frédéric Druot to renovate it. The most prominent feature is the addition of prefabricated sunspace modules outside the original building (figure 1). The architects believe that this strategy has lower price, faster construction speed and better quality than the tabula rasa method, so it is an alternative for the “demolition-reconstruction” policy implemented in Paris from 2003 [2]. The original building had a concrete frame structure. During a renovation in the 1980s, thermal insulation panels were added to the exterior walls, led to the closure of balcony and reduction of window size, affecting the apartment’s natural lighting and outward views.

![Figure 1. Bois-le-Prêtre tower after renovation (www.druot.net).](image)

After renovation, the building area and number of tenants increased. By creating a sunspace and continuous balconies to expand living areas, the comfort level, natural lighting and outward landscape of the apartments were improved. The prefabricated expansion unit has a total depth of 3 meters, including 2 meters sunspace and 1-meter balcony. The sunspace closes the original living room by a sliding double-glazed floor-to-ceiling window; itself is closed by a transparent polycarbonate sliding wall panel. It is an unheated space, which serves as a buffer space and double skin for thermal and sound insulation. The architects claim it is a delightful space for residents to use most of the year. This double-skin façade system also includes a specially designed curtain as part of comfort improving method. Due to the addition of the sunspace, energy consumption has been reduced by 50% [3]. In order to avoid residents to move out during the transformation, repeated and prefabricated lightweight steel structural modules were used to ensure the efficiency of construction. Each module measures 7 x 3.2 m. They were refabricated in factory, transported to the site by truck and superimposed together. After the modules were installed, the original exterior wall is removed and replaced with floor-to-ceiling windows.

2.2. La Chesnaie Apartment
Lacaton & Vassal also renovated La Chesnaie apartment in Saint Nazaire (France) between 2006 and 2014. This 10-storey apartment building has 40 apartments, the original structure is an industrialized construction method of tunnel formwork, the exterior wall has been renovated at the end of the last century. After renovation, the original bathroom was used as storage room, and a bedroom next to the exterior wall was converted to bathroom. New bedroom is included in a prefabricated 33 m² steel structure expansion unit also with 2 meters sunspace and 1-meter balcony, and the non-load bearing exterior wall was demolished and replaced with bay windows. The architect even integrated a new structure with extra 40 apartments on the gable of the existing building. All have sunspace, balconies, bathrooms with natural light, and sliding bay windows.
2.3. Social Housings in Bordeaux
Lacaton & Vassal and Frédéric Druot collaborated again in 2011 to transform three social residential buildings with 530 apartments in Bordeaux. The renovated building also has an extended sunspace and balcony, with the same construction detail as the Paris case, so the building has more natural light, more flexible space and more views (figure 2). The architect believes that it has renewed the typology of urban housing, and made the living conditions of residents more comfortable and pleasant. The new sunspace improves thermal comfort and reduces energy consumption significantly [4]. All three cases have the same typical renovation method as shown in figure 3.

![Figure 2. Interior of social housings in Bordeaux (www.druot.net).](image)

3. Energy Consumption Simulation
Sunspace is a typical passive solar design. In China, related research mainly focuses on its influences on the comfort of indoor thermal environment of farmhouses in cold regions and heating conservation of residential buildings in solar-rich areas in winter. Dang Qi analysed the influencing factors of thermal performance of sunspace in Inner Mongolia, and pointed out that the window-to-wall ratio is an important design factor, which determines how much heat is obtained [5]. Li En’s research shows that sunspace can significantly reduce winter heating consumption of residential buildings, and a north-south oriented sunspace should be set up [6].
In European studies, Bataineh and Fayez argued that using sunspace when facing south could minimize heating loads. It not only has the potential for energy conservation, but also has a positive impact on the shape of the original building, but the use of sunspace is closely related to the design of adequate ventilation and sun protection in summer [7]. Hilliaho studied the impact of different types of sunspace on energy consumption. Studies have shown that the in northern area can save more energy than in southern area, and the energy saving study by kilowatt hour gives a better idea of the true significance of sunspace in a building than a percentage-wise analysis [8].

The above cases and related studies show that the addition of sunspace is an effective renovating method for existing residential buildings, while the prefabricated construction method has a positive impact on shortening the construction period. However, there are few cases of this kind of renovation in China, and domestic scholars have no related research on the use of sunspace in high-rise residential buildings. Prefabricated unit mainly involves structural and constructional issues; this article is mainly focused on the energy-saving feasibility of this method in certain climate regions in China.

3.1. Simulation Condition Setting
Software selection: This paper selects numerical simulation technology and chooses DesignBuilder software, which has the characteristics of reliable calculation results, strong visualization ability, and simple modelling [9]. Model establishment: In order to have simplified research object, three hypothetical room units with same width of 4.2 meters, height of 2.7 meters and different depths of 5.1 meters, 6.6 meters, and 8.1 meters were established according to the common dimensions of living room (figure 4). The units are faced to south direction and will be retrofitted with sunspace and then compared with original condition and conventional renovation method and other variants. Simulated location: This paper selects Xi’an (latitude 34 °N) where the author is located as the main simulated city. And Beijing (latitude 40 °N), Taiyuan (latitude 38 °N) and Lanzhou (latitude 36 °N) were selected as comparative cities. According to Chinese regulation, all four cities are in cold regions, but Taiyuan and Lanzhou belong to Area 2A, and Xi’an and Beijing belong to Area 2B, where summer ventilation must be considered in addition to winter insulation.

Outdoor calculation parameters: These parameters directly access the meteorological data of each city in the Chinese Standard Meteorological Database (CSWD) included in the software, including winter and summer design climate and typical meteorological year data. Indoor calculation parameters: The heating setpoint temperature is set to 21 °C in winter, and cooling setpoint

Figure 4. Simulation model.
temperature is set to 25 °C in summer. The energy consumption simulation not only simulates the annual energy consumption, but also the typical summer and winter periods. The summer calculation period is set from 1th July to 31th August, and the winter calculation period is set from 15th November to 15th March in the next year. Room internal interference setting: The building type is set as a multi-story housing, and living mode is selected with density of two people, the metabolic rate of the human body is set to 0.9, the average clothing thermal resistance is set to 1.27, and default indoor lighting setting is selected. Air circulation is set to 5 times per hour. Envelope construction detail: Adiabatic blocks are set around the units, so it is assumed that the living units and the surrounding unit do not conduct heat transfer. Envelope construction detail is shown in table 1. Heating and cooling system settings: electricity is set as main power supply, average operating efficiency of the equipment is set to 0.6, and operating time is set in combination with heating and cooling characteristics and living customs.

Table 1. Envelop construction detail.

| Code | Envelop layer | Construction detail (from outside to inside) | U-Value (W/m² K) |
|------|--------------|---------------------------------------------|-----------------|
| Wa1  | Original wall | 20 mm plaster, 240 mm burned brick, 20 mm plaster | 2.044           |
| Wa2  | Original wall with insulation | 80 mm EPS insulation panel, 190 mm concrete block, 20 mm plaster | 0.411           |
| Win1 | Original window | 6 mm single clear window, wooden frame | 5.778           |
| Win2 | Inside window of sunspace (original wall window replacement) | 6+13+6 Dbl low-E window, aluminium frame with thermal break | 1.761           |
| Win3 | Outside Window of Sunspace | 6 mm single clear window, aluminium frame with thermal break | 5.778           |

3.2. Simulation Group One
The first group of simulations selected Xi’an, Beijing, Taiyuan, and Lanzhou as simulation locations. Five modes were set for three different depth rooms (figures 5 and 6):

- Mode A: The original state, the wall (Wa1) is not insulated, and the window (Win1) is a single layer of glass. mode B: Renovate the original state, add insulation panel to the outer wall (Wa2), and replace the window with double-glazed low-E glass (Win2). mode C: Add 2 meters deep sunspace and 1-meter balcony. Insulation panels added to the original wall (Wa2). The original window is replaced with a large double-glazed low-E glass window (Win2). The outer window of the sunlight room is 6mm single glass (Win3). This mode is called objective renovation mode in this paper as it is similar to the construction detail with previous cases. mode D: Similar to mode C, the original window size remains unchanged but its material is changed to double-glazed low-E glass (Win2), the external window of the sunspace is also 6mm single-layer glass (Win3). The original window remains unchanged, in order to simulate masonry or concrete buildings that windows cannot be expanded. mode E: The difference from mode C is that no balcony is added.

(1) Annual Energy Performance
It can be seen that for four different cities with three different depths of original units, mode B, i.e. the conventional retrofitting method can drastically reduce the annual energy consumption, but mode C, with sunspace added not only increases usable area, the energy consumption is reduced by almost 50% compared to the mode A. But it should be aware that in mode C will increase energy consumption of lighting.
Comparing the simulation results of Xi’an and Beijing, for the three different depth units, the mode with the least energy consumption is actually mode D, but this mode cannot make more use of the landscape through enlarged window. The simulation results of Lanzhou and Taiyuan are the same at room depth of 5.1 m, but at room depth of 6.6 m, the lowest energy consumption in Lanzhou is mode E, and the lowest energy consumption in Taiyuan is mode C; at room depth of 8.1 m, the lowest energy consumption of Lanzhou and Taiyuan is mode E. This not only illustrates that that the gain and loss of heat of a room is related to its size and the size of the window, and the presence or absence of balcony (acting as sunshade) also has a significant effect on the room’s heat gain and loss. In order to further analyse its performance, situations of different cities in winter and summer period were further simulated.

Figure 5. Energy consumption of different modes in four cities (5.1 m depth room). Due to limitation of article space, the charts only show the energy consumption performance of the original room at a depth of 5.1 meters.

Figure 6. Energy consumption of different modes in four cities (5.1 m depth room).

(2) Winter Energy Performance
In the winter simulation, mode C’ was added, as the natural ventilation of the original room and the sunspace was closed compare to mode C. To summarize the common points of all winter simulations: first of all, energy consumption is further reduced when natural ventilation is closed. However, to ensure the air freshness of indoor space, this mode does not occur in reality, but it illustrates the importance of ensuring the air tightness of the room. Secondly, for all simulation units, the lowest energy consumption is mode E, which means when there is no balcony, more sunlight could enter indoor space to reduce heating consumption in winter. And there is also some situation that does not have regularities: when room depth is 5.1 m and 6.6 m, only Xi’an had lower consumption when the original windows remain unchanged, all other cities’ consumption have increased. It seems to indicate that other three cities can get more heat in winter through larger windows, thus reducing energy consumption. However, at a depth of 8.1 m, if the original windows remain unchanged, the energy consumptions are reduced for all cities.

(3) Summer Energy Performance
Mode C" and mode F were added in summer simulation. The former is to add louver shades behind the outer window of the sunspace, and it is set to close automatically when the outdoor temperature reaches 26 °C; Mode F means outer window is fully opened in the sunspace considering invite more natural ventilation. Throughout all simulation results, the energy consumption has been further reduced under the conditions of adding louver shades (mode C") and the original window remain unchanged (mode D). For Xi’an, Beijing and Taiyuan, the energy consumption is the lowest at mode C". But the lowest energy consumption in Lanzhou is that the original windows remain unchanged (mode D), indicating sunshine is not strong in Lanzhou. For all cities, if there is no balcony, the energy consumption is increased compared to mode C, but the highest energy consumption is mode F in which the outer window is kept open.

In addition, the indoor temperature simulation results of mode B and C in all cities are compared. For the room as a whole, mode C is indeed hotter than mode B. But in mode C the room is divided into two parts: original room and sunspace. Actually, the original room temperature was basically the same as in mode B, but the temperature of the sunspace in mode C did appear higher than the outside dry-bulb temperature. The necessity of adjusting shading or ventilation of the sunspace was explained.

### 3.3. Simulation Group Two

In order to explore the relationship between the depth of sunspace and energy consumption, in the state of having a balcony, energy consumption was simulated while the depth of sunspace reduced to 1.1 m from 3 m, and reduced by 0.1 m each time. This group of simulations only takes Xi’an as an example.

For three different depths of the original room, the same simulation results appeared: as the depth of the sunspace decreased, the cooling consumption generally increased, but a low value point occurred at the depth of 2.6 m and 1.7 m; as the depth of sunspace decreases, heating consumption generally decreases, a high value point also occurred at the depth of 2.6 m and 1.7 m. At the depth of 1.7 m, the energy consumption for cooling is the lowest, while the energy consumption for heating is also the highest. The energy consumption for cooling and heating presents a symmetrical pattern along a horizontal line. The overall energy consumption for cooling and heating shows an increasing trend with decreasing depth, but if the energy consumption for lighting is considered, it shows a downward trend. At the same time, it can be seen from the simulation that for the same depth of sunspace, when the depth of the original room increases, the energy consumption for cooling, heating, and lighting all increases, but the increase in heating energy consumption is relatively large.

### 3.4. Simulation Group Three

In order to find out whether different wall and window constructions and their corresponding heat transfer coefficients have an impact on the energy consumption of the research subjects. The third group of simulations carried out while the original exterior wall (interior wall of the sunspace) and the exterior wall of the sunspace contain or not contain insulation materials (Wa1 or Wa2); and window is double low-E or single clear (Win1 or Win2). Energy consumption is simulated as wall type and window type are cross-combined. The energy consumption was simulated with a depth of 2 meters sunspace and 1-meter balcony in Xi’an.

Table 2 only shows the energy consumption performance when the room depth is 5.1 meters. However, for three different depth rooms, the lowest overall energy consumption in the whole year is always scheme No. 1, but the lowest heating energy consumption is always scheme No. 3, and the lowest cooling energy consumption is always scheme No. 13. But compared to scheme No.1, their cooling and heating energy consumption are not significantly different. Scheme No. 2 or mode C, as the objective mode of this study, is only the fifth energy-saving scheme for the whole year. The top three are all schemes that use double-glazed insulating glass both inside and outside, and the fourth is the lowest heating energy consumption scheme No. 3. In the previous renovation case, the exterior windows of the sunspace were made of polycarbonate. Because of the need for ventilation, it was often opened, so no expensive insulation glass was used. At the same time, scheme No. 8 with the
poorest thermal insulation performance among all construction types is also more energy-efficient than mode B, indicating that sunspace plays an excellent role in energy saving.

Table 2. Energy consumption of combination of different envelope construction (kWh)\(^a\).

| No | Inside wall type | Outside wall type | Inside window type | Outside window type | Full year | Summer | Winter | Lighting |
|----|------------------|-------------------|--------------------|---------------------|----------|--------|--------|----------|
| 1  | insulated        | insulated         | Dbl Low-E          | Dbl Low-E           | 855.31   | 425.87 | 317.7  | 111.67   |
| 2  | insulated        | insulated         | Dbl Low-E          | Sgl Clr             | 939.11   | 437.36 | 390.0  | 111.67   |
| 3  | insulated        | insulated         | Sgl Clr            | Dbl Low-E           | 934.89   | 507.72 | 315.5  | 111.67   |
| 4  | insulated        | insulated         | Sgl Clr            | Sgl Clr             | 1084.05  | 534.87 | 437.5  | 111.67   |
| 5  | non-insulated    | non-insulated     | Dbl Low-E          | Dbl Low-E           | 951.84   | 450.46 | 386.3  | 114.46   |
| 6  | non-insulated    | non-insulated     | Dbl Low-E          | Sgl Clr             | 1049.77  | 470.22 | 465.0  | 114.46   |
| 7  | insulated        | non-insulated     | Sgl Clr            | Dbl Low-E           | 1035.28  | 516.67 | 404.1  | 114.46   |
| 8  | insulated        | non-insulated     | Sgl Clr            | Sgl Clr             | 1184.92  | 549.58 | 520.8  | 114.46   |
| 9  | non-insulated    | insulated         | Dbl Low-E          | Dbl Low-E           | 895.29   | 463.31 | 319.3  | 112.6    |
| 10 | non-insulated    | insulated         | Dbl Low-E          | Sgl Clr             | 1012.66  | 478.73 | 421.3  | 112.6    |
| 11 | insulated        | insulated         | Sgl Clr            | Dbl Low-E           | 959.41   | 527.89 | 318.9  | 112.6    |
| 12 | insulated        | insulated         | Sgl Clr            | Sgl Clr             | 1129.45  | 558.76 | 458.0  | 112.6    |
| 13 | non-insulated    | insulated         | Dbl Low-E          | Dbl Low-E           | 897.02   | 413.82 | 369.6  | 113.53   |
| 14 | insulated        | non-insulated     | Dbl Low-E          | Sgl Clr             | 965.47   | 429.42 | 422.5  | 113.53   |
| 15 | non-insulated    | insulated         | Sgl Clr            | Dbl Low-E           | 1001.64  | 525.49 | 392.7  | 113.53   |
| 16 | insulated        | non-insulated     | Sgl Clr            | Sgl Clr             | 1131.93  | 552.82 | 492.5  | 113.53   |

Note: \(^a\) Location: Xi’an, Room depth: 5.1 m, Sunspace depth: 2 m (plus 1m balcony).

4. Conclusion
This study involves 4 cities, 3 different depths of original room, 20 different depths of sunspace, 16 different combinations of envelope structures, as a total of 336 simulations. Based on the above simulation results, the following conclusions were reached:

1. The sunspace addition model can significantly reduce cooling and heating energy consumption in the four cities of cold regions of China studied in this paper, and it can also increase usable area, but it must be combined with the feasibility of reconstruction, thereby extending the life of the building, increasing the economic value of the building, and improving the living quality of its residents;

2. As many scholars point out, there will be overheating problem in the sunspace in summer, so it is very important to shade and ventilate the sunspace; but the original room actually can maintain a
proper temperature. And setting internal shading is the easiest way to solve the overheating problem of the sunspace.

There are two sets of contradictory settings of the renovation method:

1. For the renovation model, the mode without balcony can reduce energy consumption in winter, but this situation will increase energy consumption in summer. And in architectural design perspective, balcony is one of the ways to enrich building facade layers and improve function;

2. For most simulation results, window expansion is beneficial for reducing energy consumption in winter, but it increases energy consumption in summer. And in architectural design perspective, bigger window is beneficial for utilizing outward views;

3. When both the inner and outer walls are added with thermal insulation layers, and its windows both uses double-glazed low-E glass can get the lowest energy consumption, but it’s obviously the most expensive one. Since the outer window is often opened in summer, there is no need to use expensive windows.

4. Heating energy consumption decreases with decreasing depth of sunspace, while cooling energy consumption is the opposite, but why minimum cooling value and maximum heating value occur at specific sunspace depths needs to be further explored.

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