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# Retrofitting High-Rise Residential Building in Cold and Severe Cold Zones of China—A Deterministic Decision-Making Mechanism

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## Supplementary Materials

### S1. Climate and Building Prototypes

*S1.1. Cold Zone*

Based on the national standards of energy efficiency of air conditioners and residential buildings, the COP of the air conditioners used in old residential buildings built in 1990s should be higher than 2.5 in Beijing [1-3]. Therefore, the study assumes that the prototype in the cold zone adopts air conditioners to provide cooling in summer and their energy efficiency (COP) is 2.5. Although there is no detailed requirement for cooling set points in severe cold and cold zones, as many locations in these areas do not have a cooling need, the standard applied to the hot summer and cold winter climates can be referenced. To reduce energy consumption in buildings, it is better to make temperature set points of heating and cooling conform to the regulations specified in energy efficient design standards, which require the indoor temperature to be set as 18°C in cold winters and 26°C in hot summers when the air conditioning system is working [4]. Hence, it is reasonable to set heating and cooling set points set at 18°C and 26°C in the prototypical apartment, and the air conditioning is always on 24 hours a day in order to be consistent with other zones in the cold and hot seasons, respectively.

The old residential buildings built in the 1990s or before have inferior building leakage levels compared to newly constructed buildings. The air leakage in the investigated apartments was more than 200 $m^3/h$ before they were improved in Beijing. Even after the refurbishment, the average infiltration rate was still more than 0.6/h [5]. The energy efficient design standards issued in the 1980s and 1990s required the air change rate of residential buildings to be no less than 0.5/h in heating-dominant zones in order to provide a good air quality for occupants [51]. This study therefore assumes for the air change rate in the prototype, which is 0.6/h in the cold zone.

The lighting design standard for residential buildings did not mention the energy efficient requirement until the latest standard issued in 2013 [6]. According to the design standard for building lighting issued in 2004, the lighting power density in residential buildings is 7 $W/m^2$ [50]. To meet the lighting requirement, the lighting density in the prototype is presumed as 7 $W/m^2$. In past years, the initial investment in RE was high and thus few old residential buildings applied solar energy to generate electricity or domestic hot water for residents. The common domestic water heater is gas-fired in the cold zone [7,49]. In Beijing, surveys involved in building retrofitting projects indicated that occupants usually employed gas-fired water heaters to provide hot water in existing residential buildings [5]. To present the situation of domestic hot water supply in existing residential buildings, the water heater in the prototypical apartment can be designed as gas-fired heater. Beijing is well-known as its high population density and high housing prices. The capita living space was around 18.7 $m^2$/person in Beijing and the average number of occupants were three in a household according to the Beijing statistics issued in 2005 [8]. This research concentrates on retrofitting existing residential buildings built in 1990s, hence, it is acceptable to assume that the occupancy density is 19 $m^2$/person and there are three people living in the prototypical apartment in Beijing. The retrofit projects in Beijing indicated that residential buildings built in the 19902 seldom utilized external shading devices to reduce the energy consumption [5]. Furthermore, the energy efficient design standard issued in the 1990s did not take the external shading devices into account in the heating-dominant zones [9], hence, there is no shading device in the apartment prototype.

### *S1.2. Severe Cold Zone*

Until 2006, the coal-fired boiler was still the dominant heating source, and it accounted for more than 68% of all heating. The average energy efficiency of such coal-fired boiler was around 0.75 according to a report on the heating system in Harbin [10]. A study on the heating efficiency and greenhouse gas emission of coal-fired boilers in Harbin also showed that heating systems in the northern China still primarily relied on coal in 2016 and the energy efficiency of this type of boiler is around 0.72 [11]. According to a report on residential retrofit projects in Harbin, the average energy efficiency of coal-fired boilers was up to 0.68 in existing residential buildings in 2012 [12]. The required minimum energy efficiency of coal-fired boilers should be 0.73 mandated by the latest energy efficient building standard issued in 2010, which is also employed to guide the thermal performance of boilers in the cold zone [4]. Therefore, the heating system of the apartment prototype can be assumed as the coal-fired central heating and its energy efficiency is around 0.74 in order to be consistent with the assumption in the cold zone, and to meet the same energy efficient standard in all heating-dominant zones.

In Harbin, the average temperature is about 23 °C in the hottest month, which means that the cooling demand in this zone is much lower than other climatic zones. Its annual average relative humidity is approximately 74% [13]. To keep the indoor comfort in summer, more than 80% of households adopt air conditioners to reduce the indoor temperature in heating-dominant zones. Occupants prefer to use the natural ventilation to provide the fresh air for the indoor environment in existing residential buildings [14]. The third national standard for the COP of air conditioners was issued in 2004 in China. There were five grades for different air conditioners with different COPs, and the middle grade was considered the average level of the COP of cooling in the air conditioner market. Its corresponding COP was 2.9, whereas the minimum requirement of the COP is 2.5. Even though an updated standard to guide the COP of cooling was issued in 2010 and requires the cooling COP to be at least 3.1 [15-16]. The minimum allowable value of the energy efficiency and energy efficiency grades for room air conditioners, it is better to deem the cooling COP as 2.5 in the prototype apartment as it is an old building and the life span of an air conditioner is more than 15 years. According to the energy efficient design standards issued in 2010, the temperature set points of air conditioning are 18°C in the winter and 26°C in the summer, respectively [4]; therefore, this study set the indoor temperature as 18°C in the heating period and 26°C in the cooling period for energy simulation. Regarding cooling demand, there is always a retired senior person at home, and it is thus necessary to maintain a comfortable indoor environment. It is assumed that cooling is continuous in the severe cold zone in order to be consistent with the assumption in the cold zone, 24 hours, in the summer and/or as needed. In fact, there is few cooling demand in the summer in the severe cold zone owing to its low average temperature in hot days, and thus the operation schedule does not have a significant impact on energy consumption for cooling.

There has been usually about 3 persons living in an apartment in Harbin since the 1990s according to the official survey data [17]. It is therefore assumed that the occupancy density in this apartment prototype is about 20 $m^2$/person, with three occupants. The lighting power density in residential buildings should be no less than 7 $W/m^2$, which is ruled by design standard for building lighting issued in 2004 [18]. From energy efficiency and economic perspectives, the gas water heater is a better choice for households than other types of water heaters. In the severe cold zone, the most popular equipment for the domestic hot water in residential buildings is gas water heaters other than electric or heat pump water heaters [19]. Accordingly, the prototypical apartment in the severe cold zone adopts gas water heater to provide hot water. Some site surveys have shown that the average air infiltration rate in old residential building built in the 1990s is around 0.24/h in Beijing and 0.98/h in Tangshan [20]. Another investigation involved in retrofit projects showed that the air infiltration rate in existing residential buildings was around 0.8/h in Urumqi, which has climatic conditions very similar to those in Harbin [21]. Meanwhile, the energy efficient standard issued in 2010 made a requirement that the infiltration rate should be no less than 0.5/h in the severe cold and cold climates [22]. As a sequence, the study assumes that the air change rate in the prototypical apartment is 0.5/h. Owing to the long winter with extremely low temperature and the short mild summer, existing residential buildings seldom employ shading devices to reduce the solar heat gain and their designs didn't take the reduction of cooling demand into account [23], To reflect the real situation of existing apartments in the severe cold zone, it is better to design the prototype without shading devices.

**S2. Decision Variables of Optimization Model**

The overall retrofit cost $C_{retrofit}$ is the sum of the costs of the selected retrofit measures, while the energy consumption $E_a$ in the renovated building depends on the thermal properties of the chosen retrofit solutions. Energy reduction is difference between the building energy consumption ($E_a$) after retrofitting and the reference energy consumption ($E_b$) before retrofitting in a building; the baseline $E_b$ is the original energy use before retrofitting. Each choice of retrofit solution can affect the total energy use $E_a$, and there is a direct relationship between the chosen retrofit techniques and a building's energy consumption. The optimal set of building retrofit solutions is composed of proper retrofit measures corresponding to the building envelope and service systems, in which a group of choices for a building component generate an appropriate solution for its renovation. The present study examines 28 potential types of retrofit techniques involving lighting, heating and cooling, energy management, solar energy use and the building envelope, etc. These techniques are defined as decision variables in the decision model, described below:

(1) The first group of choices to improve building energy efficiency relates to lighting systems:

- The first variable presents the alternative retrofit techniques used for daylighting control factor ($T1$).

Supposing that there are $n$ different types of options in the group of daylighting control measures ($T1$) to be taken into account: the binary variable is $T1_i$ with $i = 1, 2, \ldots, n$. $T1_i$ is one possible retrofit measure to control the daylighting and matches with its specific thermal property ($P_{T1_i}$) and cost ($C_{T1i}$). $P_{T1_i}$ is the thermal property of $T1_i$, which is the binary variable in the set $P_{T1}$, and $P_{T1i}$ represents $P_{T1}$ when the final decision is $T1_i$ for the renovation of the daylighting control system. The thermal property of the chosen retrofit technique $P_{T1_i}$ is one decisive factor in energy consumption for lighting $(E_a^L)$ in a building that is being upgraded. When $i = 1$, that means no retrofit measure is chosen for the building performance improvement, so the retrofit cost is zero when it selects $T1_1$ as its retrofit solution. Of a type of retrofitting alternatives, only the optimal one can be chosen to improve building energy efficiency. The relationship between this variable and the corresponding cost is defined as:

$$C_{T1} = C_{T1_i} = \begin{cases} 0, \ i = 1 \\ cost\ of\ T1_i, \ i = 2, 3, \ldots, n \end{cases} \quad (1)$$

$$P_{T1} = P_{T1_i} = \begin{cases} 1, i = 1 \\ daylighting\ factor\ of\ T1_i, i = 2,3, \dots n. \end{cases} \quad (2)$$

- The second variable presents the alternative retrofit technique for the occupancy sensors ($T2$).

This study assumes that there are be $n$ different types of options in the group of lighting occupancy control ($T2$) to be taken into account: the binary variables are $T2_j$ with $j = 1, 2, \dots, n$. $T2_j$ is one of the possible retrofit measures to control lighting according to the occupancy and matches with its specific thermal property ($P_{T2j}$) and cost ($C_{T2j}$). $P_{T2_j,}$ the binary variables describing the thermal property of $T2_j$, which can represent $P_{T2}$ (the thermal property of $T2$) when the final decision is $T2_j$ for the occupancy sensor retrofit. The thermal property of the chosen retrofit technique $P_{T2_j}$ is one decisive factor in energy consumption for lighting $(E_a^L)$ in a building being upgraded. When j=1, the retrofit measure is $T2_1$ and the building does not need any change to this lighting control. No occupancy sensor is employed in the prototype, so the investment in this retrofit measure related to the occupancy sensor is zero. This variable can also be defined in a similar fashion as seen in Equations (1) and (2).

- The third variable presents the alternative retrofit technique for the lighting constant illumination control factor ($T3$).

Supposing that there are $n$ different types of options in the group of retrofitting the lighting control system corresponding to the constant illumination ($T3$) to be taken into account: the binary variables are $T3_k$ with $k = 1, 2, \dots, n$. $T3_k$ is one of the possible retrofit measures to control lighting according to the constant illumination and matches with its specific thermal property ($P_{T3_k}$) and cost ($C_{T3_k}$). $P_{T3_k}$ is the thermal property of $T3_k$, which is the binary variable in the set of thermal properties ($P_{T3}$). $P_{T3_k}$ can represent $P_{T3}$ when the final decision is $T3_k$ for the renovation of the lighting control system regarding the constant illumination. The thermal property of the chosen retrofit technique $T3_k$ is $P_{T3_k,}$ which is one decisive factor in energy consumption for lighting $(E_a^L)$ in a building being upgraded. When $k$ =1, the retrofit measure for the control of constant illumination is $T3_1$ and there is no renovation for this type of lighting control, the retrofit cost for this aspect is therefore zero. This variable can also be defined in a similar fashion as presented in Equations (1) and (2).

- The fourth variable represents the alternative retrofit technique for lamp renovation ($T4$).

Supposing that there are $n$ different types of options in the group of retrofitting lighting lamps ($T4$) to be taken into account: the binary variables are $T4_l$ with $l = 1, 2, \dots, n$. $T4_l$ is one of the possible retrofit measures to upgrade the lighting bulbs and matches with its specific thermal property ($P_{T4_l}$) and cost ($C_{T4_l}$). $P_{T4_l}$ is the thermal property of $T4_l$, which is the binary variable in the set of the thermal property $P_{T4}$ of lamps. $P_{T4_l}$ can represent $P_{T4}$ when the final decision for the renovation of lighting lamps is $T4_l$. The thermal property of the chosen retrofit technique$P_{T4l}$ is a decisive factor in energy consumption for lighting $(E_a^L)$ in a building being upgraded. Similarly, when $l = 1$, existing buildings will continue to use their current lamps and they do not need to improve their lamps, hence, the retrofit cost for lamps will be zero. This variable can also be defined in a similar fashion as shown in Equations (1) and (2).

Based on the above retrofit selection, the energy used for lighting ($E_a^L$) can be defined as follows:

$$E_a^L = f_1(P_{T1}, P_{T2}, P_{T3}, P_{T4}) = f_1\left(P_{T1_i}, P_{T2_j}, P_{T3_k}, P_{T4_l}\right) \tag{3}$$

where $E_a^L$ denotes the energy consumption for lighting demand after building retrofits; $f_1$ is the simplified relationship between energy consumption and the thermal properties of retrofit measures in the building energy simulation, which is determined by the energy simulation logic in the EPC Calculator; $P_{T1}, P_{T2}, P_{T3}, P_{T4}$ are thermal properties of retrofit measures corresponding to $T1, T2, T3, T4$; when the optimal retrofit choices are $T1_i, T2_j, T3_k, T4_l$ from the sets of alternative retrofit measures $T1$, $T2$, $T3$, $T4$ ( $i, j, k, l = 1,2,3 \ldots n, respectively$ ); $P_{T1_i}, P_{T2_j}, P_{T3_k}, P_{T4_l}$ represent the thermal properties $P_{T1}, P_{T2}, P_{T3}, P_{T4}$ of these chosen retrofit solutions.

(2) The second group of choices to improve building energy efficiency involves mechanical systems.

- The fifth variable represents alternative retrofit techniques for the heating system ($T5$).

There can be different renovation methods for heating systems in different climatic zones. In cold zones, residential buildings use natural gas boilers to provide central heating due to the enormous heating demand. In warm zones, heating is mainly supplied by room air conditioners. Although they have different specific retrofit measures for their existing heating systems, the abstract concept for potential heating retrofit options in the optimization process is the same. Supposing that there are $n$ different types of options in the group of heating system retrofit ($T5$) to be taken into account: the binary variables are $T5_m$ with $m = 1, 2, \ldots, n$. $T5_m$ is one of the possible retrofit measures to upgrade heating systems and matches with its specific thermal properties ($P_{T5_m}$) and cost ($C_{T5_m}$). $P_{T5_m}$ is the energy efficiency of the retrofit measure $T5_m$ for the heating system. When the final decision for the renovation of heating systems is $T5_m$, $P_{T5_m}$ can represent $P_{T5}$ as $T5_m$ means $T5$ at that time. The thermal property of the chosen retrofit technique $P_{T5_m}$ is one decisive factor in energy consumption for heating ($E_a^H$) in a building being upgraded. Each retrofit measure has its specific price, and different choices of heating renovation methods will lead to different costs. This variable can also be defined in a similar fashion as presented in Equations (1) and (2).

The improvement of energy efficiency of a heating system will lead to different levels of energy consumption to meet heating demands; the retrofit choice for the heating system affects the delivered energy $E_a^H$, which can be described in a similar fashion as in Equation (3).

- The sixth variable represents the alternative retrofit techniques for the cooling system ($T6$).

In the five climatic zones of China, the common cooling system in existing residential buildings is room-unit air conditioning. Different types of room air conditioners have different COPs, and their energy consumption varies widely for the same cooling demand. Unsurprisingly, types with higher COPs have higher prices, so it is essential to balance the COP of a room conditioner and its cost when it is employed to improve the energy efficiency of a building. Supposing that there are $n$ different types of options for retrofitting the cooling system ($T6$) to be taken into account: the binary variables for $T6$ are $T6_o$ with $o = 1,2, \ldots, n$. $T6_o$ is one of the possible retrofit measures to upgrade a cooling system and matches with its specific thermal properties ($P_{T6_o}$) and cost ($C_{T6_o}$).

$P_{T6_o}$, which is the energy efficiency of the chosen cooling system $T6_o$, is the binary variable for $P_{T6}$. When $T6_o$ is the final decision for the renovation of a cooling system, $T6_o$ can represents $T6$ and its corresponding energy efficiency, $P_{T6}$ , can also be expressed as $P_{T6_o}$. The thermal property of the chosen retrofit technique $(P_{T6_o})$ is one decisive factor in energy consumption for cooling $(E_a^C)$ in a building being upgraded. The optimal retrofit measure of a cooling system is one of $T6$ based on its integrated benefits of cost and energy saving. This variable can also be defined in a similar fashion as seen in Equations (1) and (2).

The improvement in cooling system COPs will lead to different energy consumption to meet cooling demands, and the retrofit choice for a cooling system affects the delivered energy $E_a^C$ , which can be described in a similar fashion as in Equation (3).

- The seventh variable represents alternative retrofit techniques for the building energy management system (BEMS) ($T7$).

In older existing residential buildings, it is rare to use computer-based control systems to manage building energy efficiency, so this study assumes that there is no BEMS in existing high-rise apartments. Supposing that there are $n$ different types of options for BEMS ($T7$) to be taken into account: the binary variables for $T7$ is $T7_p$ with $p = 1, 2, \ldots n$. $T7_p$ is one of the possible retrofit measures to utilize BEMS for existing buildings and matches with its specific energy-efficient property ($P_{T7_p}$) and cost ($C_{T7_p}$). $P_{T7_p}$is the binary variable for the energy-efficient property ( $P_{T7}$) of a BEMS and $C_{T7_p}$ is the binary variable for the cost $C_{T7}$ of the BEMS technique ($T7$). When the chosen BEMS solution is $T7_p$ for retrofitting existing buildings, $T7_p$ can represent $T7$ and its the energy-efficient property $P_{T7_p}$ stands for $P_{T7}$, therefore, the cost $C_{T7_p}$ of the chosen solution $T7_p$ can represent $C_{T7}$ for the retrofit decision-making process. The energy-efficient property of the selected retrofit technique ($P_{T7_p}$) is one decisive factor in energy consumption for heating and cooling $(E_a^H and\ E_a^C)$ in a building being upgraded. When $p = 1$, no BEMS will be employed in the prototype. This variable can also be defined in a similar fashion as seen in Equations (1) and (2).

The better energy-efficient property of a BEMS can lead to a lower energy consumption used for heating and cooling, so the retrofit choice for BEMS affects the delivered energy $E_a^H\ and\ E_a^C$, which can be described in a similar fashion as in Equation (3).

(3) The third group of choices to improve building energy efficiency involves renewable energy (RE) technologies employed for the building retrofit.

- The eighth variable represents the alternative retrofit techniques for solar water heaters ($T8$).

The average height of high-rise residential buildings in different climatic regions varies across China. The limited roof area restricts the use of solar energy, and the most common application is to use solar solutions for domestic hot water (DHW) in China. Due to the hot water demand and available roof areas, different volumes of solar hot water with different solar collector arrays may be used in different climatic zones. Supposing that there are $n$ different types of options for solar hot water heaters ($T8$) to be taken into account: the binary variable is $T8_q$ with $q = 1,2, \ldots, n$. $T8_q$is one potential retrofit option for solar hot water heaters and matches with its specific thermal properties $P_{T8_q}$ and cost $C_{T8_q}$. $P_{T8_q}$, the binary variable for the set ($P_{T8}$) of solar collector arrays of solar hot water heaters, can represent $P_{T8}$ when the final decision on the renovation of DHW system is $T8_q$. $C_{T8_q}$, the binary variable for the cost $C_{T8}$ of alternative solar hot water heaters, can represent the cost $C_{T8}$ when choosing $P_{T8_q}$ as the final retrofit solution on solar water heaters ($P_{T8}$). The thermal property of the chosen retrofit technique $P_{T8_q}$ is one decisive factor in energy consumption $(E_a^{DHW})$ for DHW in a building being upgraded. The optimal retrofit decision for solar water heaters is one of $T8_q$, based on its balanced benefits of cost and energy conservation. This variable can also be defined in a similar fashion as seen in Equations (1) and (2).

The effect of using solar heat as the energy source for DHW can be described in a similar fashion as in Equation (3).

(4) The fourth group of choices to improve building energy efficiency refers to the building envelope retrofit

- The ninth to twelfth variables represent four orientations of wall insulation ($T9$ on the south, $T10$ on the north, $T11$ on the east, $T12$ on the west).

Different thicknesses of insulation materials can be used on the walls to improve the building's thermal performance. With each orientation, it is assumed that there are $n$ different options of insulation thickness for the wall retrofit to be taken into account: the binary variable is $T9_r$ with $r = 1,2, \dots, n$ on the south; the binary variable is $T10_s$ with $s = 1,2, \dots, n$ on the north; the binary variable is $T11_t$ with $t = 1,2, \dots, n$ on the east; the binary variable is $T12_u$ with $u = 1,2, \dots, n$ on the west. $T9_r$ is one potential retrofit option for wall insulation on the south, with $r = 1,2, \dots, n$, and its specific thermal properties and cost are presented as $P_{T9_r}$ and $C_{T9_r}$. Similarly, $T10_s$, $T11_t$ and $T12_u$ are the potential renovation options for wall insulation on the north, east and west, respectively. $P_{T9_r}$ is the thermal property of $T9_r$, which is the binary variable for the set ($P_{T9}$) of thermal property of insulated walls on the south. When the final decision for retrofitting walls on the south is $T9_r$, the thermal property $P_{T9_r}$ of the selected wall insulation ($T9_r$) can represent $P_{T9}$ and the corresponding cost $C_{T9_r}$ can stand for $C_{T9}$. Based on the same logic as $P_{T9_r}$, the binary variables for the sets ($P_{T10}$, $P_{T11}$, $P_{T12}$) of thermal properties of insulated walls are $P_{T10_s}$, $P_{T11_t}$ and $P_{T12_u}$ on the north, the east and the west, respectively. $P_{T10_s}$, $P_{T11_t}$ and $P_{T12_u}$ are the thermal properties of the corresponding techniques including $T10_s$, $T11_t$ and $T12_u$. When the chosen techniques for wall insulation are $T10_s$ on the north, $T11_t$ on the east and $T12_u$ on the west, $P_{T10_s}$, $P_{T11_t}$ and $P_{T12_u}$ can represent $P_{T10}$, $P_{T11}$ and $P_{T12}$, therefore, $C_{T10_s}$, $C_{T11_t}$ and $C_{T12_u}$ can stand for $C_{T10}$, $C_{T11}$ and $C_{T11}$ in the decision-making process. The thermal properties $P_{T9_r}$, $P_{T10_s}$, $P_{T11_t}$, $P_{T12_u}$ of the chosen retrofit techniques $T9_r$, $T10_s$, $T11_t$ and $T12_u$ make up one group of decisive factors in energy consumption for cooling and heating $(E_a^H \; and \; E_a^C)$ in a building being upgraded. The corresponding cost $C_{T9_r}$, $C_{T10_s}$, $C_{T11_t}$, $C_{T12_u}$ of the chosen retrofit techniques $T9_r$, $T10_s$, $T11_t$ and $T12_u$ make up four groups of decisive factors in the investment in the wall insulation on four orientations $C_{T9}$, $C_{T10}$, $C_{T11}$, $C_{T12}$, in a building being upgraded. The thermal properties of insulation choices are related to the U-value of the walls. The optimal thickness of wall insulation facing each direction is one of the potential retrofit decisions for each wall. Different thicknesses require different investments and save different quantities of energy. These variables can also be defined in a similar fashion as in Equations (1) and (2).

The improvement of a wall's U-value will lead to higher building thermal performance and thus reduce the heating and cooling demand; the retrofit choice for wall insulation affects the delivered energy $E_a^H$ and $E_a^C$, which can be described in a similar fashion as in Equation (3).

- The thirteenth to sixteenth variables present the alternative window retrofit measures on four orientations ($T13$ to the south, $T14$ to the north, $T15$ to the east, $T16$ to the west).

As discussed in section 4.3, there are many types of window glazing, such as single, double, triple and low-e glazing, in the construction market, and different climatic conditions need different window glazing for energy efficiency and cost effectiveness. In addition, windows with different orientations can gain different solar heat levels; even in the same orientation, solar heat gain can vary due to different climatic conditions. In order to obtain the greatest energy efficiency and cost effectiveness, the optimal window retrofit solution could vary with different orientations in the same climatic region. For each direction, it is assumed that there are *n* different choices of insulation thickness for the wall retrofit. $T13_v$ is one potential retrofit option for south-facing window retrofit with $v = 1,2,\ldots,n$, and its specific thermal properties and cost are presented as $P_{T13_v}$ and $C_{T13_v}$. Similarly, $T14_w$, $T15_x$ and $T16_y$ are the potential renovation options for windows facing the north, east and west, respectively. $P_{T13_v}$ is the thermal property of $T13_v$, which is the binary variable for the set ($P_{T13}$) of thermal properties of upgraded south-facing windows. $P_{T13}$ is the thermal property of the window retrofit techniques $T13$ on the south. When the final decision is $T13_v$ for the renovation of south-facing windows, the thermal property $P_{T13_v}$ of the selected window retrofit solution ($T9_r$) can represent $P_{T13}$ and the corresponding cost $C_{T13_v}$ can stand for $C_{T13}$ in the decision-making process. Based on the same logic as $P_{T13_v}$discussed above, $P_{T14_w}$, $P_{T15_x}$ and $P_{T16_y}$ are the corresponding thermal properties to $T14_w$, $T15_x$ and $T16_y$, which are the binary variables for the sets ($P_{T14}$, $P_{T15}$, $P_{T16}$) of thermal properties of windows on the north, the east and the west, respectively. When the final decisions for window retrofit are $T14_w$ on the north, $T15_x$ on the east and $T16_y$ on the west, $P_{T14_w}$, $P_{T15_x}$ *and* $P_{T16_y}$ can represent $P_{T14}$, $P_{T15}$, $P_{T16}$, therefore, $C_{T14_w}$, $C_{T15_x}$ and $C_{T16_y}$ can stand for $C_{T14}$, $C_{T15}$ and $C_{T16}$ in the optimization process. The thermal properties $P_{T13_v}$, $P_{T14_w}$, $P_{T15_x}$, $P_{T16_y}$of the chosen retrofit techniques $T13_v$, $T14_w$, $T15_x$, $T16_y$ make up one decisive factor in the energy consumed for cooling and heating $(E_a^H \; and \; E_a^C)$ in a building being upgraded. The corresponding cost $C_{T13_v}$ $C_{T14_w}$, $C_{T15_x}$, $C_{T16_y}$of the chosen retrofit techniques $T13_v$, $T14_w$, $T15_x$, $T16_y$ make up four groups of decisive factors in the investment in window renovation on four orientations $C_{T3}$, $C_{T14}$, $C_{T15}$, $C_{T16}$ in a building being upgraded. The thermal properties of window retrofit choices are related to their U-values and the SHGC of energy-efficient windows. The optimal type of window glazing in each direction is one of alternative window retrofit measures. These variables can also be defined in a similar fashion as in Equations (1) and (2).

Renovated window glazing with better thermal properties will lead to higher building thermal performance and thus reduce heating and cooling demand; the retrofit choice for window glazing improvement affects the delivered energy $E_a^H$ and $E_a^C$, which can be described in a similar fashion as in Equation (3).

- The seventeenth to twentieth variables represent the alternatives regarding overhangs on the four orientations ($T17$ on the south, $T18$ on the north, $T19$ on the east, $T20$ on the west)

Due to variations in solar radiation in the different orientations, different external shading devices are required to reduce solar heat gain, particularly in warm climates. The projection of an overhang determines the shading effect on the indoor environment and the energy saving caused by the reduction in cooling demand. The best retrofit solution for shading devices has to consider the shading effect and cost, so there will be different optimal sizes for overhangs on the different orientations of a given building. For each orientation, it is assumed that there are $n$ different projections for overhangs. For instance, $T17_z$ is one potential retrofit option for overhangs on the south, with $z = 1, 2, \ldots, n$, and its specific thermal properties and cost are presented as $P_{T17_z}$and $C_{T17_z}$. $P_{T17_z}$ is the binary variable for the set ($P_{T17}$) of the shading reduction factor (SRF) of overhangs on the south. When the final decision for the renovation of overhangs on the south is $T17_z$, the SRF $P_{T17_z}$ of the selected overhang solution ($T17_z$) can represent $P_{T17}$ and the corresponding cost $C_{T17_z}$ can stand for $C_{T17}$ in the decision-making process. Similarly, $T18_a$, $T19_b$ and $T20_c$ are the potential renovation options for overhangs on the north, the east and the west, respectively. Based on the same logic as $P_{T17_z}$ mentioned above, $P_{T18_a}$, $P_{T19_b}$ and $P_{T20_c}$ are the corresponding SRFs to $T18_a$, $T19_b$ and $T20_c$, which are the binary variables for the sets ($P_{T18}$, $P_{T19}$ ,$P_{T20}$) of SRFs of overhangs on the north, the east and the west, respectively. When the final choices for overhang retrofits are $T18_a$ on the north, $T19_b$ on the east and $T20_c$ on the west, $P_{T18_a}$, $P_{T19_b}$ and $P_{T20_c}$ can represent $P_{T18}$, $P_{T19}$ ,$P_{T20}$, therefore, $C_{T18_z}$, $C_{T19_b}$ and $C_{T20_c}$ can stand for $C_{T18}$, $C_{T19}$ and $C_{T20}$ in the optimization process. The characteristics $P_{T17_z}$ ,$P_{T18_a}$, $P_{T19_b}$ and $P_{T20_c}$of the chosen retrofit techniques $T17_z$, $T18_a$, $T19_b$ and $T20_c$ make up one group of the decisive factors in energy consumption for cooling and heating ($E_a^H$ $and$ $E_a^C$) in a building being upgraded. The corresponding cost $C_{T17_z}$ ,$C_{T18_a}$, $C_{T19_b}$ , $C_{T20_c}$of the chosen retrofit techniques $T17_z$, $T18_a$, $T19_b$, $T20_c$ make up four groups of decisive factors in the investment in overhangs on four orientations in a building being upgraded. These variables can also be defined in a similar fashion as in Equations (1) and (2).

External overhangs are beneficial in reducing cooling demand but may lead to increases in heating demand during cold seasons. While retrofitting overhangs have different effects on energy use for cooling and heating, the retrofit choice for the projection of external overhangs affects the delivered energy $E_a^H$ and $E_a^C$, which can be described in a similar fashion as in Equation (3).

- The twenty-first to twenty-fourth variables represent the alternative choices regarding side fins on the four orientations ($T21$ on the south, $T22$ on the north, $T23$ on the east, $T24$ on the west)

As with overhangs, side fins have different impact on the reduction of solar heat gain in different orientations. Indeed, even different projections of side fins in the same orientation can lead to variations in energy consumption. To make the optimal decision for a building retrofit, it is necessary to analyse the best set of fins in terms of optimal investment and energy reduction on each orientation. With each orientation, it is assumed that there are $n$ different projections for side fins. For instance, $T21_d$ is one potential retrofit option for side fins on the south, with $d = 1,2, \ldots, n$, its specific thermal properties and cost are presented as $P_{T21_d}$ and $C_{T21_d}$ . $P_{T21_d}$ is the binary variable for the set ($P_{T21}$) of SRF of side fins on the south, which denotes the SRF of $T21_d$. When the final decision for the renovation of side fins on the south is $T21_d$, the SRF $P_{T21_d}$ of the selected side fins ($T21_d$) can represent $P_{T21}$ and the corresponding cost $C_{T21_d}$, can stand for $C_{T21}$ in the decision-making process. Similarly, $T22_e$, $T23_f$ and $T24_g$ are the potential renovation options for overhangs on the north, the east and the west, respectively. Based on the same logic as $P_{T21_d}$ discussed above, $P_{T22_e}$, $P_{T23_f}$ and $P_{T24_g}$ are the binary variable for the sets ($P_{T22}$, $P_{T23}$, $P_{T24}$) of SRF of side fins on the north, the east and the west, respectively. When the final decisions for side fins are $T22_e$ on the north, $T23_f$ on the east and $T24_g$ on the west, $P_{T22_e}$, $P_{T23_f}$ and $P_{T24_g}$ represent $P_{T22}$, $P_{T23}$, $P_{T24}$, therefore, $C_{T22_e}$, $C_{T23_f}$, $C_{T24_g}$ can stand for $C_{T22}$, $C_{T23}$, $C_{T24}$ in the optimization process. The characteristics $P_{T21_d}$, $P_{T22_e}$, $P_{T23_f}$ and $P_{T24_g}$ of the chosen retrofit techniques $T21_d$, $T22_e$, $T23_f$ and $T24_g$ make up one group of decisive factors in energy consumption for cooling and heating ($E_a^H$ *and* $E_a^C$) in a building being upgraded. The corresponding cost $C_{T21_d}$, $C_{T22_e}$, $C_{T23_f}$, $C_{T24_g}$ of the chosen retrofit techniques $T21_d$, $T22_e$, $T23_f$, $T24_g$ make up four groups of decisive factors in the investment in side fins on the four orientations $C_{T21}$, $C_{T22}$, $C_{T23}$, $C_{T24}$ in a building being upgraded. These variables can also be defined in a similar fashion as in Equations (1) and (2).

External side fins are helpful in reducing cooling demand but may increase heating demand in cold weather. Although adding side fins on windows has different effects on energy use for cooling and heating, the retrofit choice for the projection of external side fins affects the delivered energy $E_a^H$ and $E_a^C$, which can be described in a similar fashion as in Equation (3).

- The twenty-fifth to twenty-eighth variables represent the alternative choices regarding internal shading devices for four orientations ($T25$ on the south, $T26$ on the north, $T27$ on the east, $T28$ on the west)

There are many types of internal shading devices in the construction market, and they make different contributions to reducing cooling demand. Additionally, placing the same internal device in different orientations could lead to variations in solar heat gain. For the purpose of optimal energy conservation and investment, choosing different internal shading devices for different orientations is beneficial. With each orientation, it is assumed that there are $n$ different types of internal shading devices. On the south, the binary variable for alternative internal shading measures is $T25_\beta$ which is one potential retrofit decision with respect to internal shading devices ($T25$) on this direction, with $\beta = 1,2,\ldots,n$, the specific thermal properties and cost of $T25_\beta$ are presented as $P_{T25_\beta}$ and $C_{T25_\beta}$. $P_{T25_\beta}$ is the SRF of $T25_\beta$, which is the binary variable for the set ($P_{T25}$) of SRF of internal shading devices on the south. $P_{T25}$ is presented as $P_{T25_\beta}$ when the final decision is $T25_\beta$ for the renovation of internal shading devices on the south. The design logic for the internal shading devices on the south is applied to other orientations. $T26_\theta$, $T27_\eta$ and $T28_\psi$ are the potential renovation options for internal shading devices on the north, the east and the west, respectively.

$P_{T26_\theta}$, $P_{T27_\eta}$ and $P_{T28_\psi}$ are the corresponding SRF to $T26_\theta$, $T27_\eta$ and $T28_\psi$, which are the binary variable for the sets ($P_{T26}$, $P_{T27}$ , $P_{T28}$) of SRF of internal shading devices on the north, east and west, respectively. $P_{T26}$, $P_{T27}$ , $P_{T28}$ can be represented by $P_{T26_\theta}$, $P_{T27_\eta}$ and $P_{T28_\psi}$ when the final retrofit choice for internal shading devices are $T26_\theta$ on the north, $T27_\eta$ on the east and $T28_\psi$ on the west. The SRFs $P_{T25_\beta}$, $P_{T26_\theta}$, $P_{T27_\eta}$ and $P_{T28_\psi}$ of the chosen retrofit techniques $T25_\beta$, $T26_\theta$, $T27_\eta$ and $T28_\psi$ make up one group of the decisive factors regarding energy consumption for cooling and heating $(E_a^H \ and \ E_a^C)$ in a building being upgraded. The optimal choice of shading systems for each direction represents one alternative for internal shading devices: $T25_\beta$ on the south, $T26_\theta$ on the north, $P_{T27_\eta}$ on the east, $P_{T28_\psi}$ on the west. The corresponding cost $C_{T25_\beta}$, $C_{T26_\theta}$, $C_{T27_\eta}$, $C_{T28_\psi}$ of the chosen retrofit techniques $T25_\beta$, $T26_\theta$, $T27_\eta$, $T28_\psi$ make up four groups of decisive factors in the investment in internal shading devices on the four orientations $C_{T25}$, $C_{T26}$, $C_{T27}$, $C_{T28}$ in a building being upgraded. These variables can also be defined in a similar fashion as in Equations (1) and (2).

Internal shading devices contribute to the reduction of cooling demand but may be harmful to energy conservation in zones that require heating. Internal shading devices have different effects on energy use for cooling and heating, and the retrofit choice for the SRF of internal shading devices affects the delivered energy $E_a^H$ and $E_a^C$, which can be described in a similar fashion as in Equation (3).

**Table S1.** Optimum retrofit measures in the cold zone.

| Optimum Retrofit Measures in the Cold Zone | | | |
|---|---|---|---|
| **Building Systems** | **Groups of Potential Retrofit Options** | **Optimum Retrofit Techniques** | **Original Components** |
| Lighting system | T1-daylighting control | Fully automatic control | No daylighting control |
| | T2-lighting occupancy control | Fully automatic control | No occupancy control |
| | T3-constant lighting control | No retrofit | No constant lighting control |
| | T4-lighting lamps | LED | Fluorescent lamps |
| Air conditioning system | T5-heating system | Pipe system retrofit | Gas boiler without controlling |
| | T6-cooling system | No retrofit | Air conditioner with 2.5 COP |
| | T7-BEM system | C-adapting operation | No BEM system |
| Re | T8-solar water heater | No retrofit | Electricity water heater |
| External wall | T9-insulation on south | 50 mm EPS | No insulation on 300 mm concrete block wall |
| | T10-insulation on north | 50 mm EPS | No insulation on 300 mm concrete block wall |
| | T11-insulation on east | 100 mm EPS | No insulation on 300 mm concrete block wall |
| | T12-insulation on west | 50 mm EPS | No insulation on 300 mm concrete block wall |
| Window system | T13-window retrofit on south | 6/12 mm double low-e glazing | 5 mm single clear glazing |
| | T14-window retrofit on north | 6/12 mm double low-e glazing | 5 mm single clear glazing |
| | T15-window retrofit on east | 6/12 mm double low-e glazing | 5 mm single clear glazing |
| | T16-window retrofit on west | 6/12 mm double low-e glazing | 5 mm single clear glazing |
| Internal shading | T25-shading on south | No retrofit | No internal shading |
| | T26-shading on north | Venetian blind | No internal shading |
| | T27-shading on east | No retrofit | No internal shading |
| | T28-shading on west | Venetian blind | No internal shading |

**Table S2.** Economic analysis of building retrofits in the cold zone.

| Economic analysis of building retrofit for 60% energy saving in the cold zone | | | | | |
|---|---|---|---|---|---|
| **Retrofit Measures** | **Retrofit Cost (USD)** | **Saved Energy Use (kWh/m²/year)** | **Energy Saving Per Cost (kWh/USD)** | **NPV of Saved Energy Cost (USD)** | **NPV of Optimal Benefits (USD)** |
| Fully daylighting control | 60 | 319 | 100 | 12110 | 8,530 |
| Fully occupancy control | 30 | | | | |
| LED | 30 | | | | |
| Pipe retrofit of heating system | 630 | | | | |
| C-adapting operation | 1,400 | | | | |
| 50 mm EPS on south | 50 | | | | |

| | | | | | |
|---|---|---|---|---|---|
| 50 mm EPS on north | 170 | | | | |
| 100 mm EPS on east | 270 | | | | |
| 50 mm EPS on west | 170 | | | | |
| 6/12 double low-e on south | 190 | | | | |
| 6/12 double low-e on north | 320 | | | | |
| 6/12 double low-e on east | 100 | | | | |
| 6/12 double low-e on west | 130 | | | | |
| Venetian blind on north | 20 | | | | |
| Venetian blind on west | 10 | | | | |
| Total | 3,580 | 319 | 100 | 12,110 | 8,530 |

(Source: calculated results based on Table S1).

**Table S3.** Investment (USD) in retrofits for various energy-saving goals in the cold zone.

| **Investment in Retrofit for Various Different Energy-Saving Goals in the Cold Zone (USD)** | | | | | | |
|---|---|---|---|---|---|---|
| **Applied Retrofit Measures** | **20% Energy Saving** | **30% Energy Saving** | **40% Energy Saving** | **50% Energy Saving** | **60% Energy Saving** | **70% Energy Saving** |
| Daylighting control | 60 | 60 | 60 | 60 | 60 | 60 |
| Occupancy control | 30 | 30 | 30 | 30 | 30 | 30 |
| LED | 30 | 30 | 30 | 30 | 30 | 30 |
| Heating system | 0 | 0 | 630 | 630 | 630 | 630 |
| Cooling system | 0 | 0 | 0 | 0 | 0 | 2,040 |
| BEM | 0 | 0 | 0 | 1,400 | 1,400 | 2,700 |
| Solar water heater | 0 | 0 | 0 | 0 | 0 | 720 |
| Wall insulation on south | 50 | 50 | 100 | 0 | 50 | 100 |
| Wall insulation on north | 100 | 100 | 170 | 100 | 170 | 420 |
| Wall insulation on east | 0 | 80 | 80 | 0 | 270 | 330 |
| Wall insulation on west | 170 | 330 | 170 | 140 | 170 | 400 |
| Window retrofit on south | 0 | 0 | 0 | 0 | 190 | 190 |
| Window retrofit on north | 0 | 200 | 200 | 320 | 320 | 320 |
| Window retrofit on east | 80 | 100 | 100 | 100 | 100 | 100 |
| Window retrofit on west | 120 | 130 | 130 | 130 | 130 | 130 |
| Internal venetian blind on south | 0 | 0 | 0 | 0 | 0 | 0 |
| Internal venetian blind on north | 0 | 0 | 0 | 0 | 20 | 0 |
| Internal venetian blind on east | 0 | 0 | 0 | 0 | 0 | 0 |
| Internal venetian blind on west | 0 | 0 | 0 | 0 | 10 | 0 |
| Total | 640 | 1,110 | 1,700 | 2,940 | 3,580 | 8,200 |

**Table S4.** Optimum retrofit measures in the severe cold zone.

| **Optimum Retrofit Measures in the Severe Cold Zone** | | | |
|---|---|---|---|
| **Building Systems** | **Groups of Retrofit Options** | **Optimum Retrofit Techniques** | **Original Components** |
| Lighting system | T1-daylighting control | Fully automatic control | No daylighting control |
| | T2-lighting occupancy control | Fully automatic control | No occupancy control |
| | T3-constant lighting control | No retrofit | No constant lighting control |
| | T4-lighting lamps | LED | Fluorescent lamps |
| Air conditioning system | T5-heating system | Pipe system retrofit | Gas boiler without controlling |
| | T6-cooling system | No retrofit | Air conditioner with 2.5COP |
| | T7-BEM system | B-adapting operation | No BEM system |
| Re | T8-solar water heater | 200 L solar water heater | Gas-based water heater |
| External wall | T9-insulation on south | 50 mm EPS | No insulation on walls |
| | T10-insulation on north | 50 mm EPS | No insulation on walls |
| | T11-insulation on east | 50 mm EPS | No insulation on walls |
| | T12-insulation on west | 50 mm EPS | No insulation on walls |
| Window system | T13-window retrofit on south | 6/12 mm double low-e glazing | 5/5 mm double clear glazing |
| | T14-window retrofit on north | 6/12 mm double low-e glazing | 5/5 mm double clear glazing |
| | T15-window retrofit on east | 6/12 mm double low-e glazing | 5/5 mm double clear glazing |
| | T16-window retrofit on west | 6/12 mm double low-e glazing | 5/5 mm double clear glazing |
| External shading | T17-overhang on south | No retrofit | No overhang |
| | T18-overhang on north | No retrofit | No overhang |
| | T19-overhang on east | No retrofit | No overhang |
| | T20-overhang on west | No retrofit | No overhang |
| | T21-side fins on south | No retrofit | No side fins |
| | T22-side fins on north | No retrofit | No side fins |
| | T23-side fins on east | No retrofit | No side fins |
| | T24-side fins on west | No retrofit | No side fins |
| Internal shading | T25-shading on south | No retrofit | No internal shading |
| | T26-shading on north | No retrofit | No internal shading |
| | T27-shading on east | No retrofit | No internal shading |
| | T28-shading on west | No retrofit | No internal shading |

**Table S5.** Economic analysis of retrofit in the severe cold zone.

| **Economic Analysis of Building Retrofit for 60% Energy Saving in the Severe Cold Zone** | | | | | |
|---|---|---|---|---|---|
| **Retrofit Measures** | **Retrofit Cost (USD)** | **Saved Energy Use ($kWh/m^2/year$)** | **Energy Saving Per Cost (kWh/USD)** | **NPV of Saved Energy Cost (USD)** | **NPV of Optimal Benefits (USD)** |
| Fully automatic control | 70 | 335 | 67 | 13,290 | 7,470 |
| Fully automatic control | 40 | | | | |
| LED | 30 | | | | |
| Pipe system retrofit | 740 | | | | |
| B-adapting operation | 2,770 | | | | |
| 175L solar water heater | 720 | | | | |
| 50 mm EPS on south | 100 | | | | |
| 50 mm EPS on north | 80 | | | | |
| 50 mm EPS on east | 20 | | | | |
| 50 mm EPS on west | 250 | | | | |
| 6/12 mm double low-e glazing on south | 360 | | | | |
| 6/12 mm double low-e glazing on north | 150 | | | | |
| 6/12 mm double low-e glazing on east | 140 | | | | |
| 6/12 mm double low-e glazing | 350 | | | | |

| | | | | | |
|---|---|---|---|---|---|
| on west | | | | | |
| Total | 5,820 | 335 | 67 | 13,290 | 7,470 |

(based on Table S4).

**Table S6.** Investment in retrofit for various energy-saving goals in the severe cold zone.

| **Investment on Retrofit for Various Different Energy-Saving Goals in the Severe Cold Zone (USD)** | | | | | |
|---|---|---|---|---|---|
| **Applied Retrofit Measures** | **20% Energy Saving** | **30% Energy Saving** | **40% Energy Saving** | **50% Energy Saving** | **60% Energy Saving** |
| Daylighting control | 70 | 70 | 70 | 70 | 70 |
| Occupancy control | 40 | 40 | 40 | 40 | 40 |
| LED | 30 | 30 | 30 | 30 | 30 |
| Heating system | 740 | 740 | 740 | 740 | 740 |
| Cooling system | 0 | 0 | 0 | 0 | 0 |
| BEM | 0 | 0 | 0 | 1,440 | 2,770 |
| Solar water heater | 0 | 0 | 0 | 0 | 720 |
| Wall insulation on south | 0 | 100 | 100 | 100 | 100 |
| Wall insulation on north | 50 | 80 | 160 | 80 | 80 |
| Wall insulation on east | 20 | 30 | 30 | 20 | 20 |
| Wall insulation on west | 0 | 150 | 250 | 250 | 250 |
| Window retrofit on south | 0 | 0 | 360 | 360 | 360 |
| Window retrofit on north | 0 | 0 | 150 | 0 | 150 |
| Window retrofit on east | 0 | 0 | 140 | 0 | 140 |
| Window retrofit on west | 0 | 350 | 350 | 350 | 350 |
| Internal venetian blind on south | 0 | 0 | 0 | 0 | 0 |
| Internal venetian blind on north | 0 | 0 | 0 | 0 | 0 |
| Internal venetian blind on east | 0 | 0 | 0 | 0 | 0 |
| Internal venetian blind on west | 0 | 0 | 0 | 0 | 0 |
| Total | 950 | 1,590 | 2,420 | 3,480 | 5,820 |

(calculated results based on Table S1).

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