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Building Energy Efficiency for Indoor Heating Temperature Set-Point: Mechanism and Case Study of Mid-Rise Apartment

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Abstract: Space heating accounts for a large part of building energy consumption. Lowering the heating temperature set-point (Tsp) is expected to be a feasible approach for energy efficiency. In this paper, eight globally typical cities are selected, and the energy-saving mechanism and variation trends of lowering heating Tsp are investigated under different working conditions (climate conditions, construction completion year and inner heat sources). The results show that significant energy-saving effects even appear in the relatively warm-winter cities. The energy-saving mechanism is dominated by two different categories of heating hours including the temperature-difference saving (TDS) hours and the behavioral saving (BS) hours. The contribution of TDS and BS to the whole annual heating energy saving amount (HSA) depends on the reducing level of heating hours. The HSA of lowing Tsp is mainly affected by TDS influence. After coupling the consideration of different factors, with the decreasing annual HSA of buildings, the dominance of the TDS influence mechanism shrinks gradually while the annual heating energy saving ratio (HSR) increases. This work provides the analysis method for building heating energy saving potential evaluation and reference for the establishment of standards and residents' behavioral energy saving in different climatic zones.

Keywords: temperature set-point; indoor air; building heating; energy saving; load demand

Citation: Qi, X.; Zhang, Y.; Jin, Z. Building Energy Efficiency for Indoor Heating Temperature Set-Point: Mechanism and Case Study of Mid-Rise Apartment. *Buildings* **2023**, *13*, 1189. https://doi.org/10.3390/buildings13051189

Academic Editor: Rafik Belarbi

Received: 27 March 2023
Revised: 23 April 2023
Accepted: 28 April 2023
Published: 29 April 2023

1. Introduction

With the social and economic progress of all countries around the world, sustainable development has aroused widespread concern [1], and building energy conservation is an important aspect [2–4]. In the U.S., energy consumption in commercial and residential buildings accounted for 41% of primary energy consumption in 2010, and, among the energy end-uses, space heating took up to 43% of the total building's primary energy consumption [5]. In Europe in 2015, buildings contributed significantly to the total energy consumption in all 28 European Union (EU-28) member states, corresponding to 38.9% [6]. Much of this building energy was consumed by lighting, heating, ventilation, and air-conditioning (HVAC), all of which were affected by the residents' behavior. The effect of windows on indoor air conditioning loads under different conditions was studied by K. Laskos et al. [7]. Ruey-Lung Hwang et al. [8,9] provided architects with optimal solutions for different parameters to meet thermal comfort requirements by simulating the performance of different glazing façade parameter compositions. In this regard, the indoor temperature setpoint (Tsp) is one of the most significant control parameters of human behavior, and directly affects the energy consumption of HVAC. Therefore, countries all over the world are paying more attention to building energy conservation [10–13].

It is always a key issue to determine the indoor temperature or Tsp, especially in residential buildings where the heating demand dominates and the indoor heating Tsp directly affects the building energy consumption [14]. Decreasing the heating Tsp is among the main methods to save energy [15]. Many studies have been conducted to reduce the energy consumption of indoor air conditioning and to ensure the comfort of buildings [16–20].

For the study of the optimal working conditions of air conditioning comfort and energy consumption, Ning Mao et al. [21] did an optimization study of air conditioning system operation influenced by the heat load of the envelope structure, ensuring that 1.4~17 kwh of electricity can be saved per day. Nidhal Ben Khedher et al. [22] evaluated the thermal performance of building walls combined with phase change materials in terms of indoor temperature reduction and heat transfer time delay. Adua et al. [23] simultaneously examined the relationship between householders' energy-related behavior and residential energy consumption. The home-heating temperature-setting behavior was identified as a major driver of residential energy consumption. Huang et al. [24] showed that the energy consumption of an HVAC system could be minimized through proper temperature control. According to the preferred thermal comfort range, different buildings under different climatic backgrounds have different heating Tsp values. For the building design codes and the energy-saving design standards, all countries have strict regulations on the indoor heating Tsp. The ASHRAE 55-2013 standard [25] stipulates that the indoor Tsp in winter should be 20~24 °C. The Chinese design standard for heating ventilation and air conditioning of civil buildings GB50736 stipulates that the Tsp should be 18~22 °C in long-term stay areas and 17~21 °C in short-term stay areas. In order to enhance the energy conservation of central heating systems and decentralized heating systems in public buildings, the Chinese government issued a notice on strictly implementing the air conditioning temperature control standard, which stipulates that the indoor Tsp in winter must not be higher than 20 °C. Researchers have undertaken many studies on indoor temperature setting habits. Gianniou, et al. [26] used smart meters to monitor the heating energy usage of about 14,000 households in Aarhus, Denmark, and then the linear regression method and the thermal balanced model were adopted to estimate the mean heating Tsp, which was 19.1 °C during the heating periods. Lin et al. [27] studied the load characteristics of bedrooms in tropical and subtropical areas, and the results showed that the indoor Tsp was a vital factor affecting the total energy consumption for the whole year. Gorazd et al. [28] pointed out that the most widely used concept, named as the general balance point temperature, represents the indoor Tsp (e.g., UK 15.5 °C and USA 18.3 °C). Lin et al. [29] conducted a survey on the usage of residents at night in Hong Kong, China, and the results showed that 36% of the residents slept at night with an indoor Tsp between 20 °C and 22 °C.

Researching the influence of Tsp on energy-saving, many studies have been carried out. Michal Veselý et al. [30] demonstrated that thermal comfort can be well maintained and more energy efficient at ambient temperatures 4–5 K above or below those recommended by current standards. Energy simulations show that reductions of up to 60% can be achieved. As early as 2001, Sigrimis, et al. [31] conducted research on Tsp optimization in a comparative analysis of the energy consumption of a greenhouse, and the results showed that under different climatic conditions, the energy saving rate by changing the Tsp was significantly different. Ashfaque et al. [32] analyzed the effects of climatic variation on energy utilization, and a good indication of the design features and energy efficiency requirements were provided according to the geographic location of the building. Hoyt, et al. [33] used EnergyPlus software to simulate the energy consumption of six different medium-sized office buildings in seven different cities. When the heating Tsp was reduced from 21.1 °C to 20 °C, the energy consumption of the heating systems was reduced by an average of 34%. Bionda, [34] used the building simulation program IDA ICE to predict the energy savings of a multi-family residential building in northern Switzerland. When decreasing the heating Tsp from 21 °C to 16 °C just at night, all occupied apartments achieved approximately 3~13% energy saving for the individual apartments and 6~9% for the whole building. Mohammad, et al. [35] used a mid-rise apartment as the building model to analyze the energy savings in several American cities. The results showed that using extended setpoint temperatures reduced the CO_2 emissions up to 21.4% per year.

In conclusion, although different research results showed that lowering the heating Tsp has a remarkable energy-saving effect, and the qualitative conclusions are highly consistent. However, most of the existing studies have been conducted on single buildings to study their energy-saving potential due to changes in heating setting temperature in a particular climate zone. Owing to the differing conditions of in the various research studies, it is difficult to horizontally compare the quantitative conclusions of HSR when the Tsp drops by the same amount because of the widely varying results. Existing studies lack a comparison of the energy-saving potential due to lower cross-sectional heating set temperatures in regions with different climatic differences. Only buildings in a particular climate zone are analyzed in terms of energy savings, and the essential mechanism of energy savings cannot be grasped. The mechanism of the quantitative difference in the energy-saving effect cannot be well explained by the existing research. Superficial understanding of the mechanism is not conducive to clear scientific guidance for a reasonable selection of the heating Tsp and behavioral energy conservation. Therefore, eight representative cities in different countries around the world were selected in this study, and the energy-saving effects were systematically analyzed when the heating Tsp was reduced by 1 °C. The climates of the eight cities vary greatly. Vancouver, Canada enjoys a mild and rainy climate, while New York, USA experiences a temperate and humid climate. Casablanca, Morocco has a Mediterranean climate, and London, England has a mild and rainy climate. Moscow, Russia has a temperate continental climate, while Beijing, China has a temperate continental monsoon climate. Finally, Cairo, Egypt experiences a hot and dry desert climate. These cities have different temperature ranges, levels of precipitation, and seasonal variations in their climates. Under the conditions in different climates, construction completion year, internal sources of the occupancy behavior, construction applications and the coupling of these factors, the characteristics of the energy-saving principles for reducing the heating Tsp were delivered, so as to provide theoretical reference for better realization of building conservation. The research on the energy-saving effects of lowering the heating set temperature in different regions can provide guidance and reference for appropriate energy-saving strategies and methods in building heating system design and other applications. This work can provide the analysis method for building heating energy saving potential evaluation for the establishment of standards and residents' behavioral energy saving in different climatic zones.

2. Materials and Methods

The methodology is described in this section. The steps in selection of the section are: (I) select different geographic locations as climatic backgrounds, (II) determinate the building model, and (III) determine the load forecasting method and important setting conditions.

2.1. Geographic Locations

The main factors for choosing the representative cities include: (I) consideration of the geographical representation of particular cities; (II) consideration of the typicality of the climatic zones of the cities; and (III) the differences of the annual heating demand, such as high, medium and low heating demand, among the cities. To this end, eight representative cities were selected from different countries in four continents of the northern hemisphere: Vancouver of Canada, New York of USA, Casablanca of Morocco, London of UK, Cairo of Egypt, Moscow of Russia, Beijing of China and Tokyo of Japan. This study simulated the heating load demand for the building using the current hourly weather data, the obtained from the third and the latest Typical Meteorological Year (TMY3) collection by U.S. Department of Energy [36]. Each TMY3 file contains 8760 hourly records of climate for the specific location, which was developed based on the 1991~2005 weather data. Figure 1 gives the geographical distribution of the eight representative cities, whose latitude ranges from 30° to 56°. Table 1 lists the selected cities and associated climate zones based on the ASHRAE Standard 169-2013 [37], and the eight selected cities are located in four different continents, covering different climatic conditions. The selected cities have the complexity, representativeness and typical characteristics. Among the Climate zones of No. "1~6" [37], the higher number means the higher heating demand. The selection of these eight representative major cities allows consideration of different climate conditions in order to estimate the heating demand savings for the city's climate condition. While the cities of Moscow, Vancouver, and London are heating-dominated, the other five cities require minimal or less cooling compared to the cities located in cold zones.

Figure 1. Geographical distribution of the representative cities.

Table 1. Location and climate characteristics of eight representative cities.

States	Cities	Climate Zones	Latitude N+ (°)	Longitude E+/W− (°)	Annual Average Temperature (°C)	Average Temperature of the Coldest Month (°C)	Annual Minimum Temperature (°C)	Annual Total Solar Radiation (MJ/m^2)
Asia	Beijing	3	39.80	116.47	12.65	−3.83	−14.2	5042.77
	Tokyo	5	36.18	140.42	13.06	1.95	−10.0	4704.60
Europe	London	4	51.30	0.12	7.31	−7.15	−20.6	5046.15
	Moscow	6	55.75	37.63	5.52	−7.58	−25.20	3504.07
North America	New York	4	40.78	−73.97	12.48	−1.72	−15.60	5299.55
	Vancouver	5	49.18	−123.17	9.74	3.20	−7.20	4426.26
Africa	Cairo	2	30.13	31.40	21.72	13.95	7.00	6909.36
	Casablanca	2/1	33.37	−7.58	17.32	11.43	1.00	6471.99

2.2. Building Information

This study proposes to start deployment of the setpoint decrease in a mid-rise apartment, which is a U.S. Department of Energy (DOE) Reference Building [38]. The selection of the building type empowers this study to assess the significance of the building heating demand in terms of the response to the temperature setting conditions. The research object is a three-story mid-rise apartment, and the building appearance and the floor layout are shown in Figures 2 and 3, respectively. The building's height is 12.2 m and has heating areas of 3135 m^2. The areas and thermal performance parameters of the building envelope are all given in Table 2. In Table 2, the thermal resistance and the SHGC of the building envelope are all based on the standards of Las Vegas located in 3B zone according to the calculation of DOE reference case building and the thermal performance of the building envelope is based on the existing building standards completed in the United States in 2004 [39]. The selection basis of the setting conditions is to balance the differences between different countries and different climatic zones.

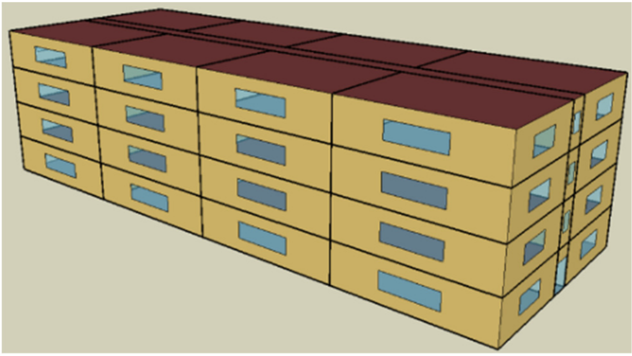

Figure 2. Building appearance.

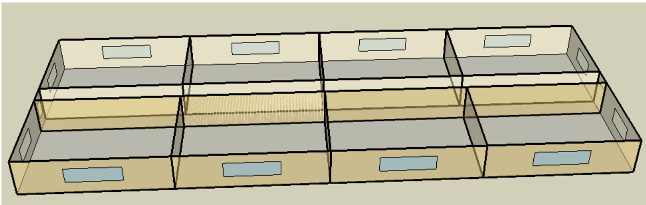

Figure 3. Floor layout.

Table 2. Building envelope areas and thermal performance parameters.

Parameters	Value	Unit
Total floor area	3135	m^2
Total area of the external envelope	2340	m^2
Building volume	9561	m^3
Shape coefficient	0.24	/
Ratio of window to wall (W&E& S&N)	0.15	/
Heat transfer coefficient of external wall	0.44	$W/m^2 \cdot K$
Heat transfer coefficient of external window	3.81	$W/m^2 \cdot K$
Heat transfer coefficient of roof	0.34	$W/m^2 \cdot K$
Heat transfer coefficient of ground	1.32	$W/m^2 \cdot K$
Solar Heat Gain Coefficient (SHGC)	0.39	/

2.3. Load Forecasting Methods

The Characteristic Temperature Method (CTM) was adopted for the research to simulate the dynamic heating load of the building, following recent papers by other researchers and verified by experiments and software comparisons [40,41]. In previous research, the author constructed the same methodology to study the energy-saving effect and mechanism when the cooling temperature setpoint was increased for residential buildings in different cities of China [41]. In this paper, more in-depth research was carried out. It was assumed that mid-rise apartments with the same thermal performance of the building envelope were built in eight worldwide representative cities with significant climatic differences, and the CTM method was used to simulate the hourly dynamic heating load of the buildings with different heating Tsp under different meteorological conditions. The influence of the heating Tsp reduction on annual heating demand reduction and the energy-saving law was investigated, and then the climate differences of the energy-saving principle of this measure were analyzed. In the simulation analysis, if the outdoor dry-bulb temperature was higher than the heating Tsp, the load will be zero. If the indoor characteristic temperature at a certain hour caused by the coupling effect of various factors was higher than the heating Tsp, the load of the hour will also be zero. Taking into account the recommended Tsp of various national standards and specifications, two cases were assumed for the heating Tsp: 20 °C and 19 °C, respectively. In order to better focus on the climate differences of the energy-saving principle, when analyzing the baseline condition, it was assumed that the thermal performance of the building envelope remained unchanged, and the internal heat sources such as indoor personnel, equipment and lighting were neglected. The 8760 h of the whole year were included in the analysis, regardless of holidays, festivals and daily schedules. The ventilation rate was set at 0.24 h^{-1}. Next, keeping the baseline condition unchanged, the U-value of envelope structures was only raised from the building level in 2004 to the new building level with better thermal insulation performance, so as to study the difference in building completion years of the energy-saving principle when lowering the heating Tsp. Furthermore, keeping the baseline condition unchanged, only the factors of the internal heat sources caused by the occupancy behavior such as personnel, lighting and equipment were added into the simulation, so as to study the difference of occupancy behavior on the energy-saving principle when lowering the heating Tsp. Finally, keeping the baseline condition unchanged, the two coupling factors of the occupancy behavior and the construction completion year were included in the simulation, and the three coupling factors of occupancy behavior, construction completion year and the work–rest schedule were also included in the simulation. The characteristics of the energy-saving principles under the coupling effect of multiple factors for lowering the heating Tsp were studied, fully revealing the energy-saving mechanism

3. Climatic Differences of Energy-Saving Principle

3.1. Comparison of Annual Energy-Saving Effects

The comparison of the annual HSA and HSR of the mid-rise apartment in eight cities with the heating Tsp lowering by 1 °C is given in Figure 4. The same mid-rise apartment has different degrees of absolute HSA under different climatic backgrounds. The colder cities usually have the higher annual HSA, and even the relatively warm-winter cities also achieve significant energy-saving effects. The reduction of the difference in HSA is sufficient to prove that lowering the heating Tsp is a universal measure to save energy in heating under different climatic conditions. However, although the annual HSA has a clear correlation to the annual heating demand, an interesting converse phenomenon is shown in the Figure 4. The reasons are analyzed from the micro-time perspectives in the following sections. In addition, the annual HSR is equal to the ratio of the annual HSA to the annual heat demand before the reduction of Tsp, therefore the cities with higher heating demand have lower HSR. Among the eight cities, Moscow has the lowest annual HSR of 6.18%. Comparing the difference between the HSA and the HSR, the warmer cities have lower HSA but higher HSR. The previous literature only focused on the relative HSR, which is one-sided to some extent, because the annual HSA is of more practical significance to sustainable development, energy cost reduction and pollutant emission conservation.

3.2. Micro-Energy-Saving Mechanism

3.2.1. Hourly Heating Load Reduction (HLR) Amount

In order to explore the climatic differences of the heating saving mechanism of heating Tsp reduction in different cities, two representative cities, Moscow and Cairo, with the greatest climatic contrast were selected to analyze the inner relationship among the change trend of the hourly heating load with the outdoor dry-bulb temperature, the solar radiation and other factors from the micro-perspectives. By analyzing the microcosmic mechanism of the hourly absolute HLR amount and hourly relative HLR rate, the climatic difference of the annual macroscopic energy-saving principle of heating Tsp reduction in different cities was revealed.

Figure 5a,b show the change law of the hourly HLR amount in Moscow and Cairo, respectively, with the change of the outdoor dry-bulb temperature when the heating Tsp drops by 1 °C, with one point representing a heating hour in the graphs. Because the other six cities have temperature differences between those of Moscow and Cairo, it can be inferred that the change laws of the other six cities are similar to Figure 5, with only slightly different horizontal ranges. The annual outdoor temperature in Moscow ranges from −25.2 °C to 30.6 °C, while that in Cairo ranges from 7 °C to 44 °C, indicating that the winter climates in the two cities are very different; however, the variation of the hourly HLR amount with dry-bulb temperatures is similar. On careful observation, there are two kinds of characteristics in the distribution of the hours with heating demand in the different cities: (I) one kind forms an approximate horizontal line, and those hours on the horizontal line reach the peak HLR amount and the corresponding outdoor dry-bulb temperature of those hours are lower than 19 °C; (II) the HLR amount of another kind is between the zero-value (on the *X*-axis) and the peak HLR amount (on the maximum horizontal line). The corresponding outdoor dry-bulb temperature of these hours includes two temperature ranges: 20~19 °C and 19 °C~'K' °C, and 'K' means a certain temperature value much higher than the minimum temperature of each city, for example, the value is about −5 °C in Moscow and about 13 °C in Cairo. Why do the cities with contrasting climates have such similar but complicated distribution characteristics?

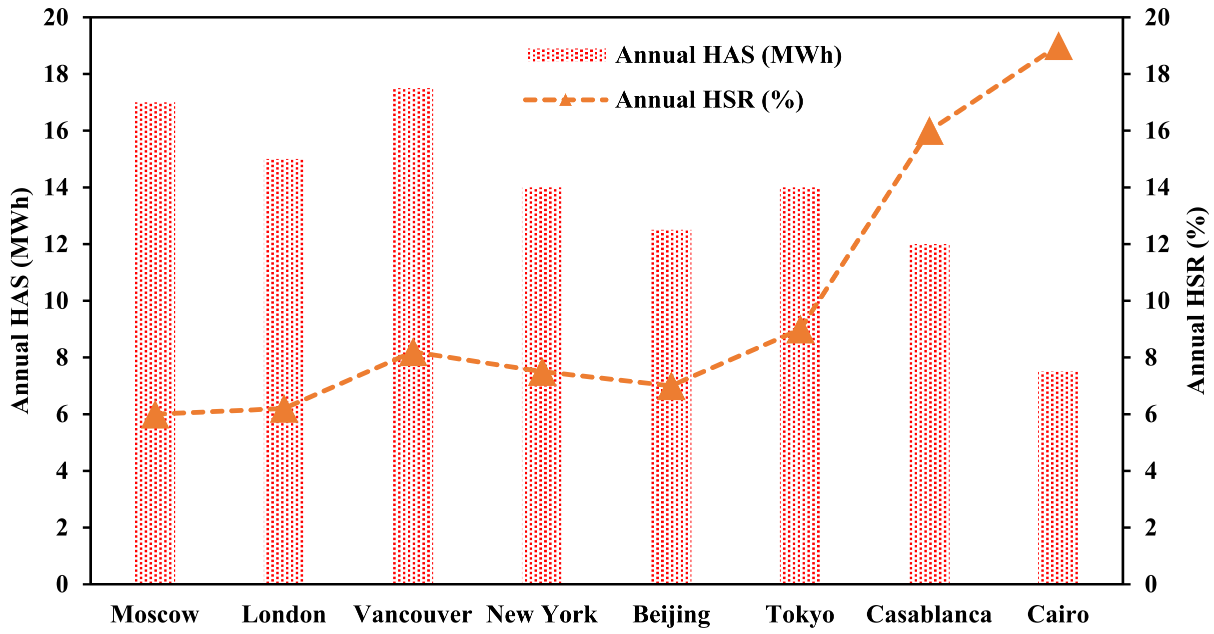

Figure 4. Comparison of annual HSA and HSR in eight cities.

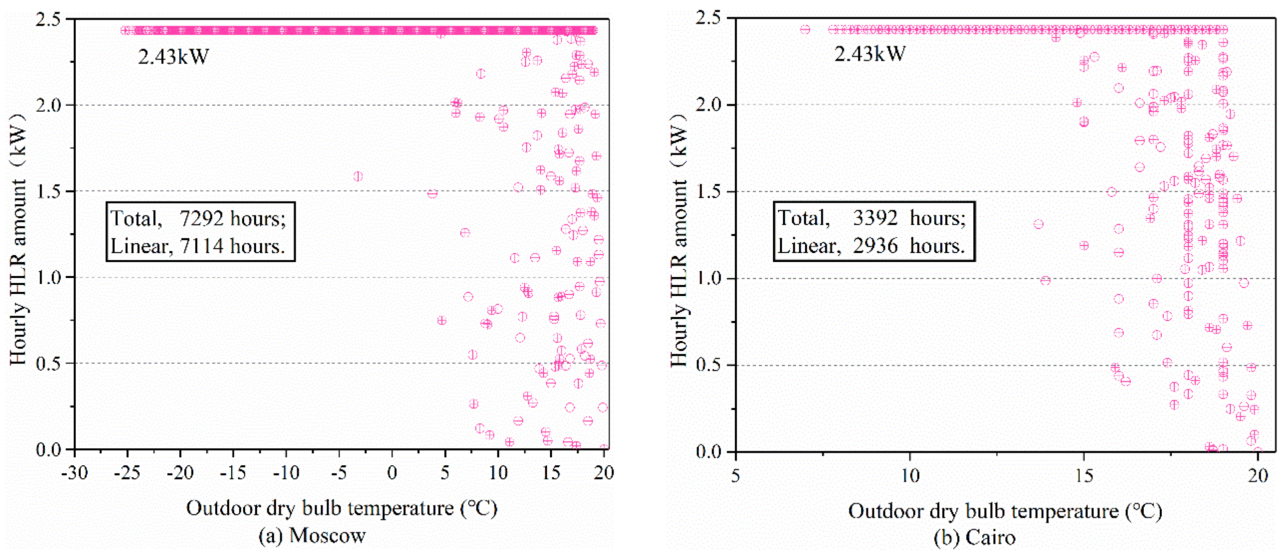

Figure 5. Distribution of the HLR amount with the change of outdoor dry-bulb temperature.

3.2.2. Microscopic Heating Saving Mechanism

Based on the in-depth study of the above two kinds of hours, there are two distinct microscopic heating-saving mechanisms:

(I) Temperature difference saving (TDS) mechanism: for the hours distributed on the approximate horizontal line, even though those hours are subject to external disturbance, internal disturbance and building envelope effects, their indoor characteristic temperatures are still lower than 19 °C, which means that in these hours there is still heating demand. The hourly HLR amount of these hours depends on the heat transfer coefficient, building areas and Tsp reduction range (1 °C in this paper). According to the characteristics of the building and the envelope in this study, the hourly HLR amount tends to a constant of about 2.43 kW, which has no correlation to the city climates. However, the cumulative TDS amount of the whole year is directly proportional to the numbers of the TDS hours, and the annual TDS amount is closely related to the city climates.

(II) Behavioral saving (BS) mechanism: for the scattered hours in Figure 5, the heating demand is small when the heating Tsp is 20 °C. Two kinds of conditions are included: one is when the outdoor temperature is between 20 °C and 19 °C, and if the Tsp is reduced from 20 °C to 19 °C, the hourly heating demand will change to be no longer needed because of changing the temperature setpoint. Another is when the outdoor temperature is lower than 19 °C, and if the indoor characteristic temperature is between 20 °C and 19 °C because of the heat gain from the solar radiation and the inner heat sources, the hourly heating demand will also change and no longer be required. The two kinds of conditions are defined as the BS mechanism. The BS amount varies widely and the cumulative annual BS amount is related to the city climates, the internal disturbance and the BS hours, the complicated mechanism is involved.

Obviously, the colder cities have more hours with heating demand but fewer BS hours, while the warmer cities have fewer hours with the heating demand but more BS hours. Furthermore, when the heating Tsp was reduced from 20 °C to 19 °C, the annual total HSA of Moscow was 17.52 MWh, of which the TDS amount was 17.31 MWh and the percentage was 98.77%. While the annual total HSA of Cairo was 7.74 MWh, of which the TDS amount was 7.14 MWh and the percentage was 92.26%. Therefore, without considering the difference of the occupancy behavior and the work–rest schedule, the energy-saving mechanism of reducing the heating Tsp is that the TDS accounts for the main contribution, and the contribution of BS is slightly higher in warm cities.

3.2.3. Hourly Heating Load Reduction (HLR) Rate

Figure 6a,b show the hourly HLR rates in Moscow and Cairo, respectively, with the change of the outdoor dry-bulb temperature. Through comparative observation, although the hours with heating demand in the two cities was greatly different, and the respective variation range of the outdoor dry-bulb temperature was also significantly different, the distribution of the hourly HLR rate in the two cities was similar. (I) All of the BS hours have a small hourly HLR amount, but they have an hourly HLR rate of 100%. (II) The rest hours are the TDS hours, although the hourly HLR amount is the same, the hourly HLR rate of them is different. Due to the big difference of the hourly heating load demand, the ratio of the hourly HLR amount to the hourly heating load demand varies widely. Under the conditions of the low outdoor temperature and no solar radiation, the HLR rate is very low. As the outdoor temperature increases, the heating load decreases, so the HLR rate increases. The approximate exponential curve formed by the minimum HLR rate corresponding to different temperatures represents the hours without solar radiation. Under the same temperature condition, the greater the solar radiation, the smaller is the heating load and the higher the HLR rate. Therefore, the variation range of the HLR rate is large under the same temperature. (III) Although the climatic difference between Moscow and Cairo is huge, the fusion of the climate between the two cities is shown, that is, the warmer months in Moscow are not substantially different from the colder months in Cairo, and the scatter distribution of Cairo can be found in the scatter distribution of Moscow. As a result, the annual HSR is close to the hours with high heating load, which is 6.18% in Moscow. While the annual HSR in Cairo also tends to the hours with high heating load, which is as high as 19%.

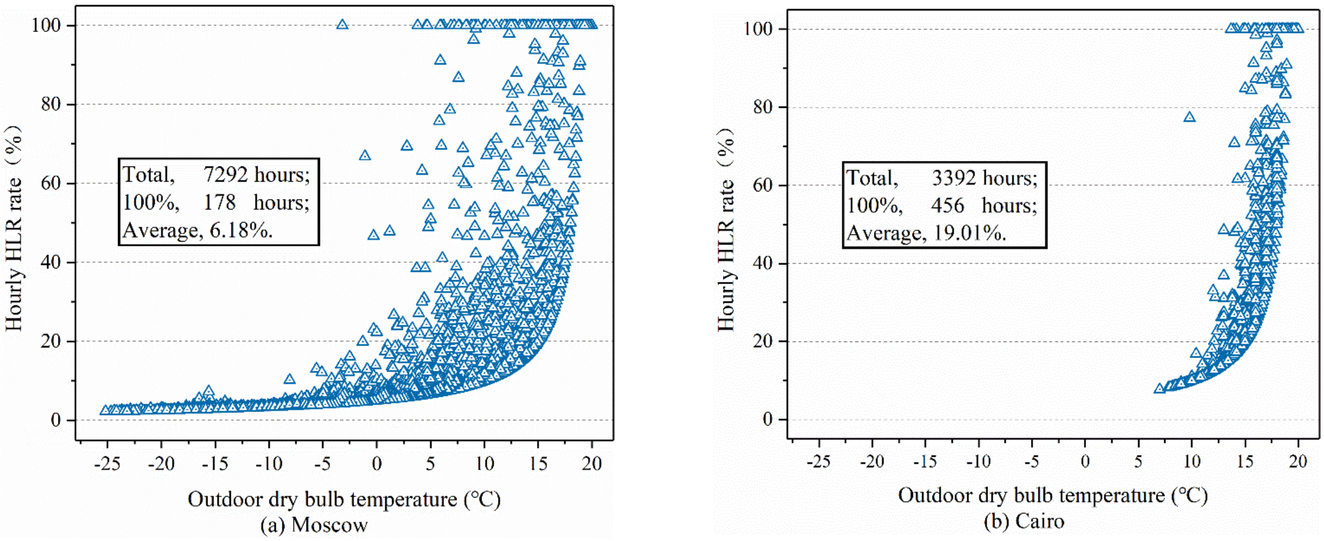

Figure 6. Distribution of the HLR rate with the change of outdoor dry bulb temperature.

3.3. Climatic Difference of Energy-Saving Principle

Table 3 gives a comparison of the statistical data of the key indicators of the annual heating energy-saving of the eight cities under the baseline conditions. The baseline conditions mean the same building, the same thermal characteristics of building envelope, regardless of internal heat sources and the work–rest schedule, and 8760 h are included in the simulation, so as to reveal the climatic difference of energy-saving principle when lowering the heating Tsp. The results show that (I) the colder cities with the lower average annual temperature generally have more heating hours through the whole year, but Vancouver is an exception. (II) The colder cities have the greater percentages of the TDS hours, while the percentages of the TDS hours drop in the warmer cities. For example, the percentage of the TDS hours is up to 97.56% in cold Moscow while dropping to 86% in warm Cairo. (III) Although the TDS hours are as low as 86% in some cities, the annual TDS amounts in different cities are all higher than 92%. By lowering the heating Tsp under the baseline conditions, the annual HSA is dominated by the TDS mechanism. (IV) The annual TDS amount depends on the numbers of TDS hours, which account for a large percentage, so the dissimilarity of annual HSA in different cities mainly depends on the dissimilarity of heating hours. (V) Similarly, the annual HSR tends to be the hours when the heating demand is large and the percentage is huge. Since the TDS amount for those hours are the same for the cities with different climates, the hourly HSR is a single-valued function that is inversely proportional to the heating load. The cities with higher heating load demand have lower annual HSR.

Table 3. Climatic difference of energy-saving principle under the baseline conditions.

Cities	Heating Hours	BS Hours	TDS Hours	TDS Hours-Percentage (%)	Annual HSA (MWh)	BSA (kWh)	TDSA (MWh)	TDSA-Percentage (%)	Annual HSR
Moscow	7292	178	7114	97.56	17.52	216.26	17.31	98.80	6.18
London	6963	237	6726	96.60	16.63	270.52	16.36	98.38	6.41
Vancouver	7350	158	7192	97.85	17.71	208.53	17.50	98.81	9.18
New York	5882	268	5614	95.44	13.92	264.84	13.66	98.13	8.08
Beijing	5397	215	5199	96.33	12.89	242.9	12.65	98.14	7.17
Tokyo	5869	387	5482	93.41	13.85	513.88	13.34	96.32	9.05
Casablanca	5280	674	4606	87.23	12.01	806.93	11.21	93.34	15.89
Cairo	3392	456	2936	86.56	7.74	599.01	7.14	92.25	19.01

4. Characteristics of the Energy-Saving Principle

4.1. Effects of New and Old Buildings Completed in Different Years

In fact, the buildings were completed in different years in all city, and the thermal performance of the building envelope is uneven. Due to the significant climatic differences and the different economic development levels, the thermal characteristics of the building envelope may be completely different, thus it is difficult for any artificial hypothesis to cover the complex conditions of the building envelope.

In order to reveal the difference of the energy-saving principle of buildings completed in different years when lowering the heating Tsp, the previous baseline conditions remain unchanged, except that the U-value of the building envelope is promoted from the level of the existing buildings in 2003 to the level of the new buildings with better thermal insulation performance, so as to study the difference of the energy-saving principle over the construction completion year. Therefore, in the simulation, the thermal resistance of the external wall of the new building is assumed as 4.81 m·K/W, the thermal resistance of the roof is 6.21 m·K/W, and the heat transfer coefficient of the external window is 1.98 W/m·K. Other setting conditions are the same as the values in Table 2.

Table 4 gives a comparison of the statistical data of the key indicators of the annual heating energy-saving in the eight cities under the conditions of new buildings with the better thermal insulation performance. Compared with the old buildings with a longer completion period (shown in Table 3), the results show that: (I) After the envelope performance is improved, the annual total heating hours in the different cities do not change much, nor do the TDS hours. (II) The reason for the huge decrease of the annual TDS amount is that the new building envelop has better thermal performance, which leads to the reduction of the hourly TDS constant value. The reason for the obvious reduction of the BS amount is similar, because the heating load between the zero-value and the TDS constant value is related to the thermal performance of the envelope structures. (III) Since the annual total heating hours and the percentages of the TDS hours in each city change slightly, the TDS amount is still the main contribution of the annual HSA. The annual HSA of the new buildings is lower when lowering the heating Tsp, indicating that old buildings with poor insulation performance have a better absolute energy-saving effects using the same Tsp energy-saving measure. (IV) Due to the linear effect of the new building envelope performance on the annual HSA reduction and the annual heating demand reduction, the annual HSR of the heating Tsp reduction is similar under the same climatic backgrounds whether it is old building or new building.

Table 4. Energy-saving principle of the new buildings in different cities.

Cities	Heating Hours	BS Hours	TDS Hours	TDS Hours-Percentage (%)	Annual HSA (MWh)	BSA (kWh)	TDSA (MWh)	TDSA-Percentage (%)	Annual HSR
Moscow	7319	187	7132	97.45	14.87	203.35	14.66	98.59	6.18
London	6959	240	6719	96.55	14.05	231.87	13.81	98.29	6.42
Vancouver	7352	165	7187	97.76	14.96	181.81	14.78	98.80	9.17
New York	5868	270	5598	95.40	11.73	225.64	11.51	98.12	8.08
Beijing	5433	225	5208	95.86	10.93	222.40	10.71	97.99	7.17
Tokyo	5865	379	5486	93.54	11.70	422.52	11.28	96.41	9.04
Casablanca	5275	669	4606	87.32	10.15	677.42	9.47	93.30	15.87
Cairo	3395	454	2941	86.63	6.54	498.01	6.05	92.51	19.01

Figure 7 shows a comparison of the hourly HLR rate in Moscow and Cairo respectively with the change of the hourly heating load under the conditions of new and old buildings with different completion year. Combined with Tables 3 and 4, for the old and new buildings with the large difference in thermal performance, the annual HSR has almost no change despite of the obvious reduction of the annual HSA. That is because, for the two cities, the annual heating hours in each city almost have no change, but due to the new building envelope, the thermal performance is better, which means the U-value is lower, so the corresponding heating saving constant of the heating saving hours is smaller, thus leading to the obvious decline in annual HSA and the heating demand. In the same city, the new and old buildings of the different completion year have similar HSR, which indicates that it is feasible for countries like China to implement the guiding policy of lowering the heating Tsp to achieve the similar HSR.

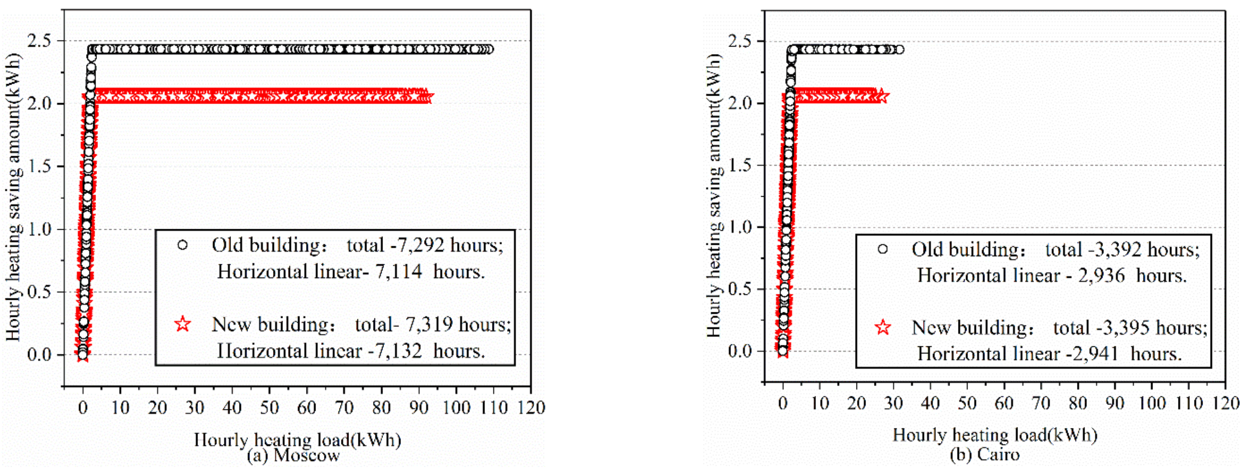

Figure 7. The hourly HSA distribution with the change of the load in old and new buildings.

4.2. Effects of the Occupancy Behavior

For any building, the work–rest schedule is different because the building function is different. Even if the building function is determined, the occupancy behavior including the occupancy rate, the accuracy of lighting, the utilization rate of the equipment and other internal heat sources are very random, so it is difficult to cover their complex changes. In order to reveal the different influence of occupancy behavior on the energy-saving principle when lowering the heating Tsp, the baseline setting condition is kept unchanged in this section except only changing the internal disturbance value according to the standards recommended for a U.S. DOE mid-rise apartment. The occupancy is assumed as 80 people, and the dissipation heating load index is 78 W per person, and 3.88 W/m^2 for lighting and 5.38 W/m^2 for equipment, and the fraction of schedules is set according to Figure 8. Other setting conditions are consistent with Table 2.

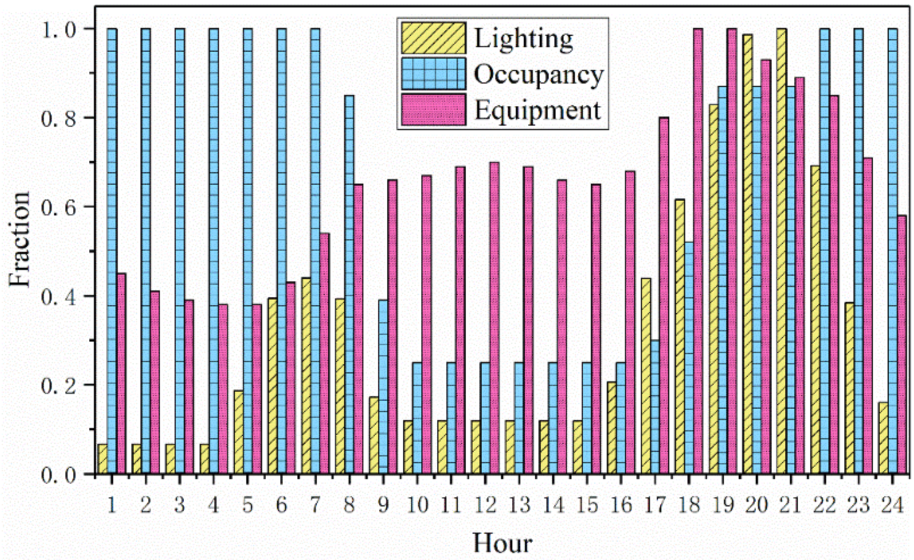

Figure 8. Fraction of schedules.

Table 5 gives a comparison of the statistical data of the key indicators of the annual heating energy-saving of the eight cities with considering the occupancy behavior and internal heat sources when lowering the heating Tsp. Compared with Table 3, the results show that: (I) Considering the internal heat sources, the annual total heating hours in different cities greatly decrease and the TDS hours obviously decrease. (II) The reason for the obvious decrease in the annual TDS amount is that the internal heat sources of the occupancy behavior led to the reduction of the annual heating hours. Although the hourly TDS constant remains stable, the heating hours decrease, so the cumulative TDS amount also decreases. (III) The percentage of the BS hours is obviously increased, resulting in a decrease in the percentage of the TDS hours from 86.56% to 71.09% in Cairo, where the percentage of the TDS hours is the lowest among all the eight cities. However, due to the higher weightiness of the TDS, the ratio of the TDS amount to the annual HSA is still large, the lowest value appears in Cairo is even as high as 82.59%. (IV) When coupled with the effect of the internal heat sources, the reduction of the annual HSA is not as huge as the reduction of the annual heating demand, so the annual HSR of all cities increases to different degrees. The warmer city has the larger increase degree. Figure 9 gives a comparison of the daily heating demand saving with the change of the accumulated daily heating consumption under the condition of considering the internal disturbance when lowering the heating Tsp 1 °C in Moscow and Cairo. The results show that after taking the heat sources of the occupancy behavior into account, the daily heating consumption in the two cities is both decreased, and the daily HSA is also decreased, which is due to the significant reduction in the daily heating hours, with a decrease of 16.18% in Moscow and 38.32% in Cairo. However, the internal heat sources have no effect on the TDS constant when the heating Tsp is reduced by 1 °C, so the annual HSR of all cities is reduced. After coupling the effects of internal heat sources of occupancy behavior, the Tsp reduction reduces the heating hours and the HSA, and increases the HSR to different degrees. The significant change of the heating saving mechanism is that the weightiness of the BS increases but the contribution of TDS weakens.

Table 5. Energy-saving principle of the occupancy behavior.

Cities	Heating Hours	BS Hours	TDS Hours	TDS Hours-Percentage (%)	Annual HSA (MWh)	BSA (kWh)	TDSA (MWh)	TDSA-Percentage (%)	Annual HSR
Moscow	5471	272	5199	95.03	13.01	363.22	12.65	97.21	8.11
London	5064	271	4793	94.65	12.00	342.08	11.66	97.15	8.32
Vancouver	4846	459	4387	90.53	11.26	586.52	10.67	94.79	15.57
New York	3851	251	3600	93.48	9.09	332.12	8.76	96.35	11.39
Beijing	3785	201	3584	94.69	8.97	247.56	8.72	97.24	9.67
Tokyo	3503	305	3198	91.29	8.15	369.15	7.78	95.47	12.85
Casablanca	1719	282	1437	83.60	3.86	362.50	3.50	90.61	24.34
Cairo	889	257	632	71.09	1.86	324.05	1.54	82.59	39.87

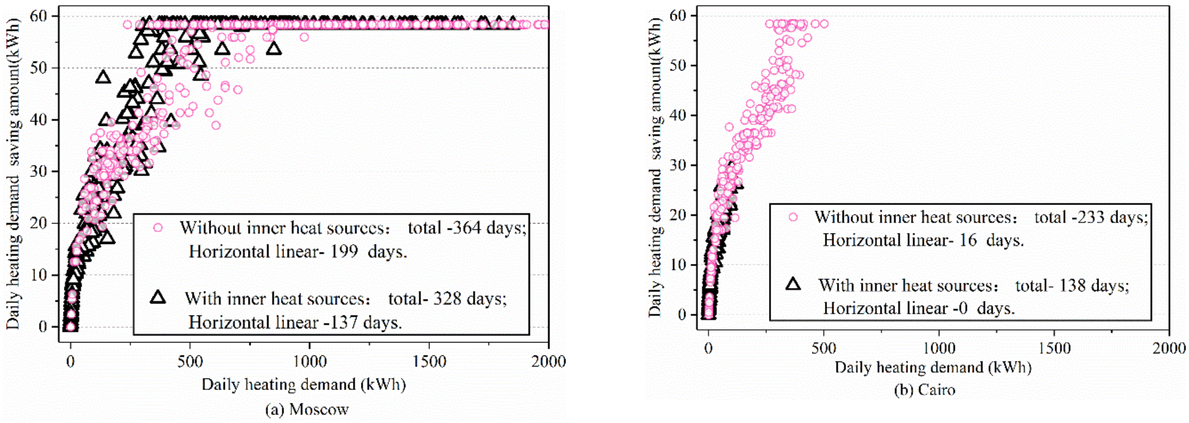

Figure 9. The daily heating demand saving amount with the change of the heating demand considering the occupancy behavior.

Figure 10 gives a comparison of the annual HSA and the percentage of the TDS amount among the four conditions: (A) only lowering the building envelope U-value; (B) only considering the internal heat sources of the occupancy behavior; (C) considering the coupling condition of the U-value reduction and the internal heat sources; and (D) the baseline condition. The energy-saving in lowering the heating Tsp has the different characteristics. As shown in Figure 10, for different conditions under different climatic backgrounds, the TDS amount is the main contributor to the annual HSA. However, compared with the baseline, under the different conditions of No. "A, B and C", the importance of the TDS amount is decreased in all cities (shown in Figure 11), and the percentage of the BS amount in the warmer cities clearly increases.

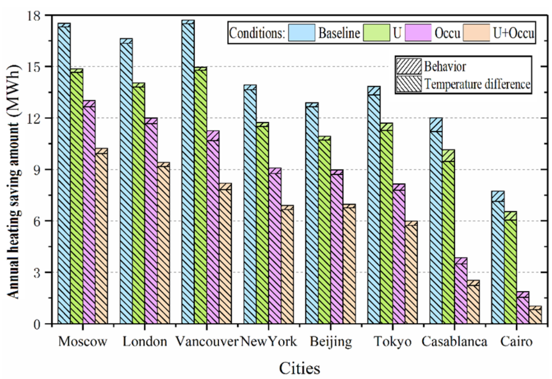

Figure 10. Comparison of annual HSA under different conditions.

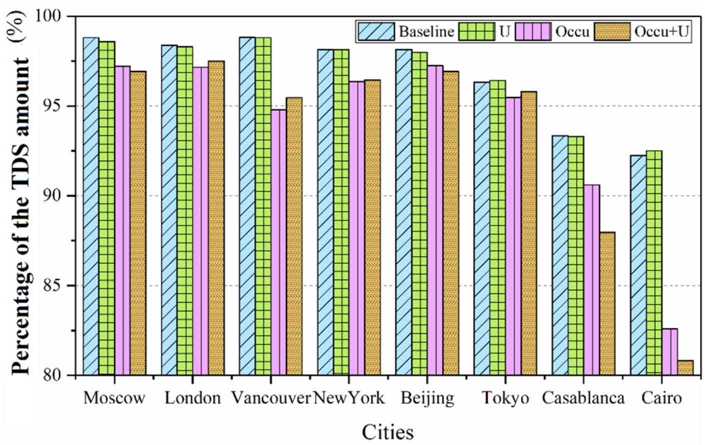

Figure 11. Comparison of percentage of TDS amount.

The above section revealed the principle of the difference in energy-saving effect of the heating Tsp reduction under the coupling factors of the different building completed periods, the different internal heat sources and the different climates (shown in Table 6). In fact, the different functions of buildings and the work–rest schedules will lead to the significant differences in operational hours. Table 7 shows the comparison of the statistical data of the key indicators of the annual heating energy-saving of eight cities considering the three factors, composed of new buildings with better thermal insulation performance, the internal heat sources of occupancy behavior and the different work–rest schedules of the mid-rise apartment. In the analysis, the operation schedule is assumed between 8:00 and 18:00, but the rest hours are not included. The internal heat sources of the occupancy behavior are set according to Figure 8, the thermal characteristics of the building envelope are set as the value of the new building, and other setting conditions are the same as the baseline value in Table 2. Compared with Table 3, after considering the coupling of the three factors, the annual heating hours and the TDS hours are both decreased, and the percentage of the TDS hours is further decreased. The annual © is decreased significantly, and the contribution of the BS is strengthened, leading to a decrease in the TDS percentage. Although the HSA in Cairo is short, 100% of it is contributed by the BS amount. When coupling the three factors, the heating load demand at night is furtherly excluded, and the reduction of the annual heating demand is larger than the annual HSA, so the annual HSR of all cities is increased again. The phenomenon of the increase of the annual HSR is more obvious in a warmer city, such as in Cairo where increased to 100%. Figure 12 gives the comparison of the annual HSA and the percentage of the TDS amount for the five conditions: (A) only considering the internal heat sources of the occupancy behavior; (B) only lowering the building envelope U-value; (C) the coupling effects of two factors; (D) the coupling effects of three factors; and (E) the baseline condition. The differences in characteristics of the energy-saving principle of lowering the heating Tsp are more obvious. As for the different conditions under different climatic backgrounds, the TDS amount is the main contributor to the annual HSA. However, compared with the baseline, under the influence of a single factor, the two coupling factors and even the three coupling factors, the importance of the TDS amount is decreased in all cities, and the BS percentage in the warmer cities is obviously increased. In the warmest city, Cairo, nearly all the HSA are contributed by the BS amount.

Table 6. Energy-saving principle of the two coupling factors.

Cities	Heating Hours	BS Hours	TDS Hours	TDS Hours-Percentage (%)	Annual HSA (MWh)	BSA (kWh)	TDSA (MWh)	TDSA-Percentage (%)	Annual HSR
Moscow	5110	283	4827	94.46	10.24	314.04	9.92	96.93	8.48
London	4701	237	4464	94.96	9.41	236.06	9.18	97.49	12.11
Vancouver	4202	393	3809	90.65	8.20	372.43	7.83	95.46	16.91
New York	3477	241	3236	93.07	6.90	245.09	6.65	96.45	8.75
Beijing	3498	210	3288	94.00	6.97	215.09	6.76	96.92	10.23
Tokyo	3037	247	2790	91.87	5.99	252.36	5.74	95.79	13.54
Casablanca	1366	277	1089	79.72	2.55	306.45	2.24	87.96	26.59
Cairo	599	194	405	67.61	1.03	197.61	0.83	80.82	47.22

Table 7. Energy-saving principle of the three coupling factors.

Cities	Heating Hours	BS Hours	TDS Hours	TDS Hours-Percentage (%)	Annual HSA (MWh)	BSA (kWh)	TDSA (MWh)	TDSA-Percentage (%)	Annual HSR
Moscow	1724	105	1619	93.91	3.44	114.63	3.33	96.80	9.06
London	1580	66	1514	95.82	3.18	71.83	3.11	97.80	9.78
Vancouver	1025	156	869	84.78	1.94	151.18	1.79	92.27	22.92
New York	1104	98	1006	91.12	2.18	111.12	2.07	94.95	14.45
Beijing	1085	80	1005	92.63	2.15	81.36	2.07	96.28	13.06
Tokyo	621	100	521	83.90	1.18	108.10	1.07	90.68	25.06
Casablanca	73	18	55	75.34	0.13	17.66	0.11	84.62	32.20
Cairo	2	2	0	0.00	0.11	1.14	0	0.00	100

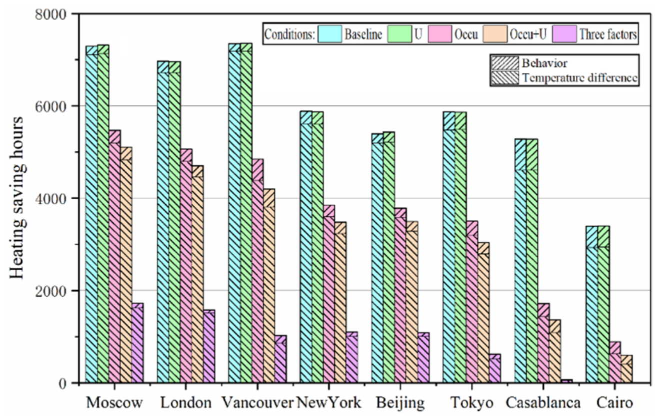

Figure 12. Comparison of heating hours under different conditions.

5. Discussion

From the above studies, the coupling influence of the Tsp reduction on the heating energy-saving effects is very complicated. When the geographic locations, the building geometry parameters, the thermal performance of envelope structures, the internal disturbance of occupancy behavior, the work–rest schedules and other parameters are different, the research results of the HSA and HSR for lowering the heating Tsp may be obtained by different researchers, so it is difficult to make the horizontal comparison as described in the introduction. Therefore, it is also difficult for scholars at home and abroad to verify the reliability of their conclusions through experiments due to such complicated coupling effects. For the object architecture selected in this paper, Kegel et al. [42] used TRNSYS software to study the annual cooling and heating load demand, the annual primary and secondary energy consumption, annual utility costs and annual greenhouse gas emissions and other results under various climatic conditions in Calgary and Canada. Since it is difficult to isolate the data of the annual HSR, only the annual heating demand in Canada in the literature was selected for the discussion. Table 8 gives a comparison of the simulation methods, the setting conditions and the simulation results between the published literature [42] and this paper. Since no specific city in Canada is mentioned in the literature, Vancouver is selected as a representative city in Canada for the climatic background. Except for the different simulation methods, other parameters such as the building, envelope and the setting conditions are all the same. Because only a general annual heating demand, including the humidification heating load to maintain the relative humidity not less than 30%, was given in the literature [42], two conditions were simulated in this paper: (I) the sensible heating load Q1-value without considering humidification and (II) the total heating load Q2-value with considering humidification.

Table 8. Comparison of the annual heating demand simulated by two methods.

Cases	Geographic Location	Building Object	Building Envelope U-Value	Personnel Lighting Equipment	Tsp (°C)	Method	Q1 (GJ)	Q2 (GJ)
Literature [42]	Canada	The same as the literature [42]			21	TRNSYS	/	675
This paper	Vancouver				21	CTM	616	698

If the humidification heating load is not taken into account, the annual sensible heating load demand Q1 simulated by the CTM method in this paper is 616 GJ, 8.7% lower than the reference value [42]. If the humidification heating load is taken into account, the simulation results showed that the annual total heating load demand Q2 is 698 GJ, which is 3.3% higher than the value in the literature. The comparative results of the above two methods are very close.

Finally, it should be pointed out that CTM is adopted in this paper and the TRNSYS software, and the simulated results of the two methods is of high consistency. The predicted annual heating demand is very close, which proves the reliability of the CTM method used in this paper, and also proves the correctness of the relevant conclusions obtained by the CTM method.

6. Conclusions and Prospects

In this paper, eight cities around the world were selected to predict the annual dynamic heating load, and then the change of the annual HSA and HSR was analyzed. Furthermore, the characteristics of the energy-saving principles are revealed, when taking the energy-saving measure of lowering the heating Tsp from 20 °C to 19 °C. The conclusions are as follows:

1. Hours with indoor temperatures below 19 °C due to external/internal disturbance and building envelope have heating demand, with the hourly heating demand depending on U-value, F-value and Tsp reduction. These hours are defined as TDS hours, and their hourly HSA tends to a constant. The fixed value of TDS hours is only related to the U-value of the building envelope, not the climatic conditions, so when the U-value is determined, the hourly TDS amount is defined as the TDS constant.
2. When the outdoor temperature is between 20 °C and 19 °C, if the Tsp is reduced from 20 °C to 19 °C, the hourly heating demand will no longer be needed because of changing the temperature setpoint. When the outdoor temperature is lower than 19 °C, if the indoor characteristic temperature is between 20 °C and 19 °C because of the heat gain from the solar radiation and the inner heat sources, the hourly heating demand will no longer be needed. Those hours in the above situations are defined as the BS hours.
3. The energy-saving effects of lowering the heating Tsp is determined by two completely different kinds of hours. One kind is the TDS hours, the hourly HSA of which is

almost a constant. Another kind is the BS hours, the hourly HSA of which is between the zero-value and the TDS constant. The annual HSA is composed of the TDS amount and the BS amount, and the annual cumulative TDS amount is proportional to the TDS hours.

4. The climatic dissimilarity in the energy-saving principle of lowering the heating Tsp is revealed. The annual TDS amount depends on the numbers of TDS hours, which account for a large percentage, so the dissimilarity of the annual HSA in different cities mainly depends on the dissimilarity of the heating hours. Similarly, the annual HSR tends to be the hours when the heating demand is large and the percentage is huge. Since the TDS amount for those hours are the same for cities with different climates, the hourly HSR is a single-valued function that is inversely proportional to the heating load. The cities with higher heating load demand have the lower annual HSR.
5. The TDS mechanism dominates the heating savings from Tsp reduction for a specific building, regardless of completed periods and internal heat sources. The annual HSA decreases with building completion, but HSR remains unchanged. Occupancy behavior decreases TDS dominance, but TDS can still account for up to 80% of savings. HSR increases to varying degrees, especially in warmer cities. When considering completed periods, occupancy behavior and work–rest schedule, TDS dominance weakens and HSR increases further. It is important to reveal the energy-saving mechanism for effective conservation and emission reduction. These findings are valuable for regional standards and resident behavioral energy-saving.

The work at this stage simply discusses typical cases to pre-estimate the building heating energy-saving potentials by lowering indoor temperature set-point under different climatic conditions. When processing and calculating the actual heating energy consumption, it will be affected by many factors, such as building type, heating equipment, climatic conditions, thermal comfort of the building environment, etc. Such limitations also arise some future research works for further investigation:

1. A mid-rise apartment is chosen as the case building here, with certain geometric and thermal parameters. Changes of building types (high-rise apartments, public buildings, factory, etc.), room geometry (location, facing direction, ratio of window to wall, etc.), and thermal properties of building envelopes (thermal conductivity, density, specific heat, solar radiation absorption ratio, etc.) can contribute to different air conditioning loads for indoor space heating.
2. Dynamic climatic conditions play a significant role in determining specific building energy consumption, in terms of dynamic temperature variation impacting both indoor load demands and thermal performance of air conditioning or heating devices. Only eight typical big cities in different climatic zones are discussed here. While for building space heating in other places including both cities and countryside located in various global climatic regions, the situations should be quite different even for the same studied building.
3. Practical building heating energy consumption also depends on the types and thermal performance of used heating equipment and systems, such as air-source heat pump, ground-source heat pump, floor radiant air conditioner, and solar thermal systems etc. In practical engineering, the building energy saving amount and rate could vary widely with different heating devices, benchmarks and reference systems, even in the same climatic zones.

Although the specific results obtained in typical cases may not meet all the conditions under different conditions, the analysis methods used in this article are general and can be applied to other occasions. This work can provide analysis approach for building heating energy saving potential evaluation and reference for the establishment of standards and residents' behavioral energy saving in different climatic zones.

Author Contributions: Conceptualization, X.Q. and Y.Z.; methodology, Y.Z.; software, X.Q. and Z.J.; validation, Z.J.; writing—original draft preparation, X.Q.; writing—review and editing, Y.Z.; supervision, Y.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This work is supported by National Natural Science Foundation of China (No. 52108032) and Sichuan Science and Technology Research Program (No. 2022NSFSC1148).

Data Availability Statement: Weather data for 3034 locations are available on website: https://www.energyplus.net/weather (accessed on 26 March 2023), including 1494 locations in the USA, 80 locations in Canada, and more than 1450 locations in 98 other countries throughout the world. The weather data are arranged by World Meteorological Organization region and Country.

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

Abbreviations

Tsp	Temperature setpoint
HSA	Heating saving amount
HSR	Heating saving rate
TDS	Temperature-difference saving
BS	Behavioral saving
HLR	Heating load reduction
SHGC	Solar Heat Gain Coefficient
CTM	The Characteristic Temperature Method

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