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Installation Principle and Calculation Model of the Representative Indoor Temperature-Monitoring Points in Large-Scale Buildings

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Abstract: Although indoor temperature was an important criterion for the evaluation of heating requirements, it was costly to install temperature-monitoring devices in every household for large-scale buildings. However, it was inexpensive to install the device at some representative locations, and the average temperature can be used to evaluate the heating requirement. In this case, it was obvious that the accuracy was limited by the location and number of installations and the calculation method. In this paper, first, the indoor temperature variation relationship between the object and adjacent households was analyzed. It was found that the correlation between the household situated above and the household in which the object was located was the strongest, which provides a new energy-saving regulation strategy. Then, the indoor temperature of households in different locations was classified using the *k*-means algorithm, and the installment location, number of representative points, and comprehensive indoor temperature calculation model were determined. Finally, the installment principle and calculation model were applied. The results show that, compared with the traditional method, the temperature obtained via the proposed method was closer to the actual temperature and was less affected by the instability of communication.

Keywords: indoor temperature; energy saving; representative points; installment principle; calculation model

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1. Introduction

Heating technology refers to the use of artificial methods to provide heating to buildings and to maintain a certain indoor temperature to create suitable living or working conditions [1,2]. Obviously, the ultimate goal of heating was to reach the target indoor temperature. With the development of heating systems, their regulation mode has gradually developed to “intelligent regulation” from “manual regulation”. This can not only reduce manual labor but can also rely on advanced technology to realize the goal of on-demand heating [3,4]. In order to achieve this goal, the most important consideration was to obtain the demand parameter, with intuitive performance judged according to whether the indoor temperature reached the target value.

For a single-household building, only one temperature-monitoring device was needed to evaluate the heating requirement. However, for large-scale buildings, which are the predominant urban residential model in China [5], it was costly to monitor every household’s temperature. Among the metered heating methods, only the wireless on–off control method needs to be installed as the indoor temperature-monitoring device [6], and other methods are not needed, e.g., the household heat meter method and temperature flow method [7]. The installation of a household heat meter has become a necessary item for the acceptance of newly constructed buildings in China, but the indoor temperature-monitoring device has not [8]. Therefore, the existing research focuses on multi-angle analysis of a household’s heating consumption rather than the indoor temperature, e.g., scholars use mathematical statistics and software simulation methods to study the variation in household heating consumption in different regions, different locations, and different enclosure structures [9–12]. The results are mainly used to correct the household's heating consumption in different locations to promote the fairness and justice of charges associated with metered heating. In addition, machine learning methods, such as the clustering algorithm, are used to classify and analyze the household's heating consumption in a certain city on a large scale [13–15] to facilitate effective district heating operations and management. Although these results provide data support for metered heating policy makers and operators of heating companies to truly understand the current situation of urban heating consumption, they do not enable the accurate evaluation of the heating requirement.

The administrators of heating systems prefer to directly and accurately evaluate the heating requirement using the indoor temperature. Therefore, they often install representative indoor temperature-monitoring points in buildings that are located at remote, middle, and near distances from the heating station. When there are a large number of households in a building, it is unfortunate that there is often a lack of detailed specifications or installation instructions to guide the installation locations. Therefore, the monitoring devices are always installed randomly, and the average value of these randomly installed monitoring points was calculated and used to evaluate the heating requirement of a building, a heating station, or a heating system [16]. However, the household's temperature was not only affected by the supplied heating but also by the location, the occupancy rate, etc. As a result, the calculated average value may not be able to accurately reflect the heating requirement. This was also the reason that a large number of temperature devices are installed at present but remain idle. Therefore, for heating company workers, the most challenging questions are as follows: Where should the representative temperature devices be installed? How should these representative devices be used to obtain a comprehensive indoor temperature that can truly reflect the heating requirement? The inability to solve these questions leads to the fact that the input parameters of the heating consumption prediction model include historical heating consumption and outdoor meteorological conditions [17–20] but not indoor temperature. Gu et al. [21] found that the comprehensive indoor temperature was a major factor affecting heating consumption. In their study, the wireless on–off control method was adopted, and the indoor temperature of each household could be obtained so the average indoor temperatures could reflect the heating requirement. The existing heating consumption prediction models are based on historical operating parameters, and the lack of indoor temperature as an input parameter will determine whether the predicted heating consumption was an economic and energy-saving value. If this was completely dependent on the historical operation, i.e., if the historical operation was over-heating, the predicted value would be higher than the demand value, and vice versa.

It was very important to obtain the comprehensive indoor temperature not only for the heating consumption prediction but also for the heating station regulation and hydraulic balance of the secondary network. For the heating station regulation, the current application methods are feed-forward regulations based on outdoor meteorological parameters [22,23]. The research shows that indoor temperature was used to correct the feed-forward regulation parameters to achieve feedback regulation, which was beneficial to improving thermal comfort and achieving energy saving [24,25]. Unfortunately, due to the lack of comprehensive indoor temperature, the feedback regulation method was seldom applied in practical engineering. For the hydraulic balance of the secondary network, unlike in Western countries, China has adopted the form of large heating stations, whose heating area usually ranges from about 50,000 square meters to 100,000 square meters. In addition, heating was supplied via the secondary network to each building entry, which sparked the hydraulic balance problem of the secondary network. As there was no parameter that could reflect the heating requirement of each building entry, the hydraulic balance was now realized via regulation experience. In recent years, some studies have adopted the return temperature to regulate the hydraulic balance among various heated building entries [26–28]. Obviously, the same return temperature does not mean that the hydraulic balance has been achieved due to different building ages, different enclosure structures, and different terminal heat dissipation devices.

In summary, both the accurate prediction of heating consumption and the precision regulation of the heating stations, as well as the hydraulic balance regulation of the secondary network systems, all require the participation of a comprehensive indoor temperature. But, for large-scale buildings, it was costly to install the temperature-monitoring device in every household but inexpensive to install the device at some representative locations. How do we choose the representative locations? How many should we install? How do we calculate the monitored temperatures to obtain the comprehensive indoor temperature? Unfortunately, there are no relevant specifications or research on these three issues. In this paper, six large-scale buildings were selected to study the installation location, number, and calculation model of the representative points.

2. Material and Methods

2.1. Case Buildings

Six buildings in Tianjin, a cold region of China, were selected as the research objects. These buildings were built in 2010, without a basement, and the energy-saving design standards meet Ref. [29]. The basic information of each building is shown in Table 1. The terminal heat dissipation device was radiator, and the form was wireless on-off control system. The operation procedure was as follows: firstly, the heat user sets the target indoor temperature using the temperature controller; then, the on-off valve detects the actual indoor temperature and determines the difference between the actual and target indoor temperature; finally, the valve calculates the proportion of on-time to off-time in the next step. The heating consumption for each household was allocated according to its heated area and the open time of the valve, as shown in Equations (1) and (2) [30].

$$q_j = \frac{\alpha_j F_j}{\sum\limits_{i=1}^{n} \alpha_i F_i} Q \tag{1}$$

$$\alpha_j = \frac{\tau_{open,j}}{\tau_0} \tag{2}$$

where F_j was the heated area of household j (m^2); α_j was the accumulative proportion of valve open time for household j; n was the number of households in the building; Q was the total heating consumption for the building; $\tau_{open,j}$ was the cumulative open time of the valve for household j; and τ_0 was the cumulative metering time of the heat meter.

Table 1. The basic information of case building.

Case Building	Total Households	Heating Households	Floors	Area (m^2)	Occupancy Rate (%)
Case 1	48	33	6	7715.35	68.75%
Case 2	24	19	6	3721.00	79.17%
Case 3	36	27	6	3815.12	75.00%
Case 4	120	96	10	13,672.4	80.00%
Case 5	80	64	10	10,412.56	80.00%
Case 6	48	29	6	7353.72	60.42%

Note. Occupancy rate refers to the ratio of heating households to total households.

2.2. Clustering

The clustering method chooses the simple and efficient *k*-means, which is an iterative analysis algorithm. The steps are as follows: the data set $X = \{x_1, x_2, x_3, \ldots, x_n\}$ was divided into k groups first, and k objects as the initial clustering center randomly selected; then, the distance between each object and the center was calculated; and each object was assigned to the cluster of its nearest clustering center. For each assigned cluster, the center was recalculated based on the existing objects in the cluster, and this process was repeated until some termination condition was met. The objective function is shown in Equation (3) [31].

$$\sum_{i=1}^{N}\sum_{k=1}^{K}\delta_{ik}\|x_i - m_k\|^2 \tag{3}$$

The calculation method of data partition matrix and cluster center update matrix was as follows:

$$\delta_{ik} = \begin{cases} 1, \forall j \neq k, \|x_i - m_k\|^2 \leq \|x_i - m_j\|^2 \\ 0, \text{other} \end{cases} \tag{4}$$

$$m_k = \frac{\sum\limits_{i=1}^{N}\delta_{ik}x_i}{\sum\limits_{i=1}^{N}\delta_{ik}} \tag{5}$$

where m_k and m_j represent the center of mass for k cluster and j cluster; δ_{ik} represents the membership of the data; if the x_i belongs to k cluster, the corresponding element value δ_{ik} was 1; otherwise, the δ_{ik} was 0.

Silhouette method was used to evaluate the similarity between the object and the sub-sets. Silhouette value was close to 1, indicating that the object was closely related to the sub-sets, and vice versa. When a data cluster has a relatively high silhouette value for a model, it proves that the model is appropriate and acceptable [32].

2.3. Traditional Installation Principle and Calculation Method

For a single-household building, the temperature-monitoring device is located in the activity area with a distance of 700–1800mm from the ground [33]. For the large-scale buildings, there was no specification for selecting which households to install a representative temperature-monitoring device, the heating company staff often adopted the principle of uniform distribution, including installation on the top household, the bottom household, the middle household, the corner household, and other households, and the number was also decided by the staff.

The average temperature $\overline{T}_{in}^{avg}$ of all representative monitoring points was calculated via average method, as shown in Equation (6).

$$\overline{T}_{in}^{avg} = \frac{\sum\limits_{i=1}^{n}T_{in}^{i}}{N} \tag{6}$$

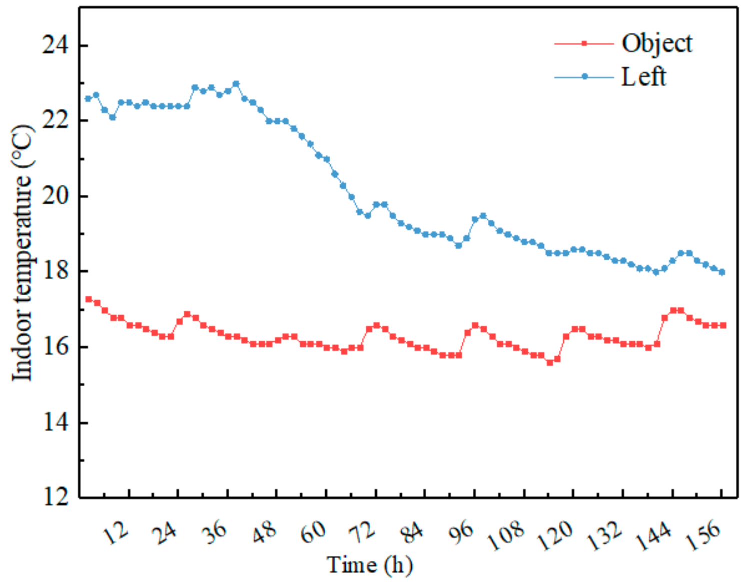
where T_{in}^{i} was the ith representative temperature-monitoring point (°C), and N was the total number of representative monitoring points.

3. Comprehensive Analysis of the Indoor Temperature

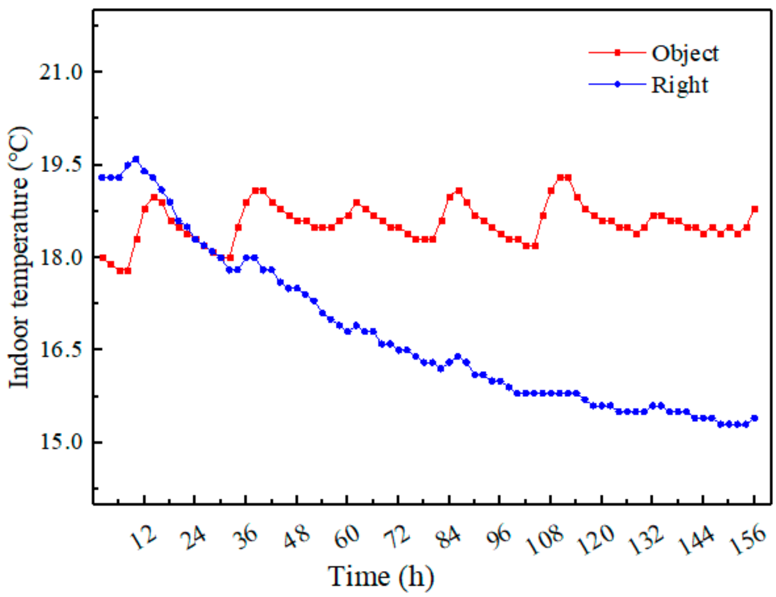
3.1. Relationship between the Indoor Temperature Variation in Object Households and Adjacent Households

In addition to outdoor temperature and heat user behavior [13,33], heat transfer between households was also a key factor affecting the indoor temperature variation for the object household. With the development of heat metering, the enthusiasm of heat users to participate in indoor temperature control was becoming higher and higher, resulting in an increasing proportion of heat transfer between households, especially for large-scale buildings [34].

During the experiment, the object household was not heated and without indoor activity or another heat source. The households situated above, below, left, and right were heated, and the valves of those households were turned on or off to analyze the influence of surrounding households on the indoor temperature variation in the object household. Previous research by our team has shown that indoor temperature variation in unheated households is not completely consistent with outdoor temperature variation, so the influence of outdoor temperature in this study was not analyzed [35]. The experiment lasted for 4 days, and the results are shown in Figure 1.

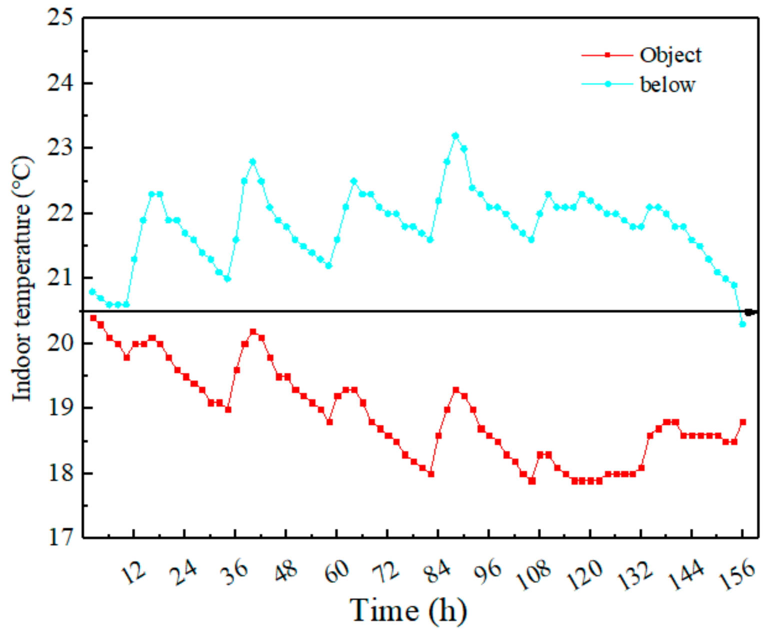


(**a**)

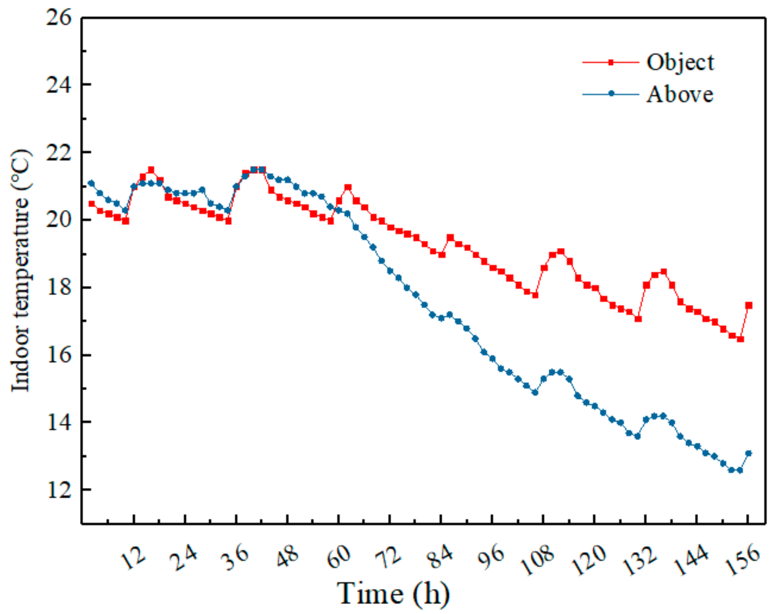


(**b**)

Figure 1. *Cont*.



(**c**)



(**d**)

Figure 1. The relationship between indoor temperature variation in objects and surrounding households. (**a**) The relationship with household situated left. (**b**) The relationship with household situated right. (**c**) The relationship with household situated below. (**d**) The relationship with household situated above.

Figure 1a,b showed that, when the valves of the household situated left and right were turned off, the indoor temperature gradually decreased. During this period, the indoor temperature of the object household showed no significant downward trend, indicating that the indoor temperature variation in the household situated left or right had little impact on that of the object household. In Figure 1c, the valve of the household situated below was also turned off, and the indoor temperature of the object household was basically negatively correlated with that of the household situated below. Compared with households situated left, right, and below, as shown in Figure 1d, after turning off the valve of the household situated above, the indoor temperature decreases sharply, and the indoor temperature of the object household also decreases gradually. Therefore, the heat of the household situated above has a great impact on the indoor temperature of the object household. This conclusion was consistent with our previous research results [35].

The above means that the heating transfer between the object household and the household situated above was the largest. Therefore, when the indoor temperature of a household fails to reach the target value, we should check the heated condition of the household situated above instead of blindly adjusting the parameters of the heating substation. If the household situated above was not heated, the valve should be opened for economical operation.

Figure 2 shows the indoor temperature variation in four heated households from 9 to 13 February in Case 1. It could be seen that the indoor temperature variation trend of the four heated households was consistent, indicating that the indoor temperature difference in different heated households was basically unchanged in the heated period.

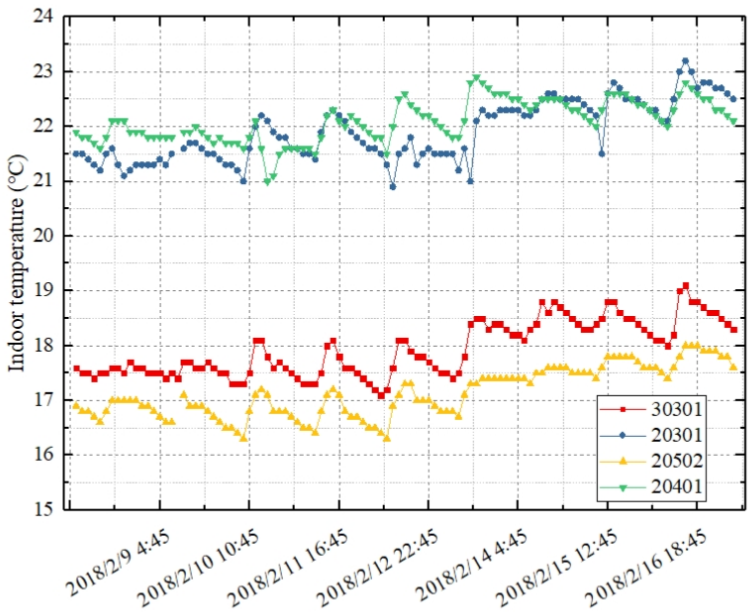


Figure 2. The indoor temperature variation in heating households in Case1.

The 20502 households complained about a low indoor temperature of 16.85 °C (yellow household in Table 2), and the indoor temperature needed to rise by 1.15 °C to reach 18 °C. According to Figure 2, the temperature difference in each heated household was unchanged, so other heated households also would rise by 1.15 °C. Before the complaint, the average indoor temperature in Case 1 was 20.31 °C, and the total heating consumption was 21,197.14 kWh. After the complaint, the indoor temperatures increased by 1.15 °C, and the total heating consumption was 22,323.58 kWh. The calculation formula was shown in Equation (8), so the heating consumption would increase by 1126.43 kWh. If we opened the valve of households situated above (20602), it only needed 660 kWh for 20502 households to reach the target temperature (18 °C), and the energy-saving rate would reach 41.4%. Therefore, in order to realize the energy-saving operation, when a household has sub-standard temperature, we should not blindly adjust the parameters of the heating substation but should analyze the reasons and then determine the adjustment strategies.

$$Q' = \left(\frac{t'_{in} - t_o}{t_{in} - t_o}\right) \times Q \tag{7}$$

where t_o was the outdoor temperature, °C; t_{in} was the original indoor temperatures, °C; t'_{in} was the correction indoor temperature, °C; and Q was the actual heating consumption, kWh. In this study, $t_o = -1.33$ °C, $t_{in} = 20.31$ °C, $t'_{in} = 21.46$ °C, and $Q = 21{,}197.14$ kWh.

Table 2. The indoor temperature and heating consumption of each household in Case 1.

<table>
<tr><td>Household number</td><td>10601</td><td>10602</td><td>20601</td><td>20602</td><td>30601</td><td>30602</td><td>40601</td><td>40602</td></tr>
<tr><td>Indoor temperature (°C)</td><td rowspan="3">Non-heated</td><td>18.94</td><td>19.19</td><td rowspan="3">Non-heated</td><td>18.82</td><td rowspan="3">Non-heated</td><td rowspan="3">Heated</td><td rowspan="3">Heated</td></tr>
<tr><td>Heating consumption (kWh)</td><td>914.22</td><td>660.9</td><td>755.71</td></tr>
<tr><td>Target indoor temperature (°C)</td><td>/</td><td>/</td><td>/</td></tr>
<tr><td>Household number</td><td>10501</td><td>10502</td><td>20501</td><td>20502</td><td>30501</td><td>30502</td><td>40501</td><td>40502</td></tr>
<tr><td>Indoor temperature (°C)</td><td>14.85</td><td>14.86</td><td>20.33</td><td>16.85</td><td>21.69</td><td></td><td rowspan="3">No heating</td><td>22.2</td></tr>
<tr><td>Heating consumption (kWh)</td><td>687.64</td><td>0</td><td>352.82</td><td>649.95</td><td>865.4</td><td>761.68</td><td>489.85</td></tr>
<tr><td>Target indoor temperature (°C)</td><td>/</td><td>/</td><td>20</td><td>/</td><td>/</td><td>/</td><td>/</td></tr>
<tr><td>Household number</td><td>10401</td><td>10402</td><td>20401</td><td>20402</td><td>30401</td><td>30402</td><td>40401</td><td>40402</td></tr>
<tr><td>Indoor temperature (°C)</td><td>18.93</td><td rowspan="3">Heated</td><td>21.95</td><td rowspan="3">Non-heated</td><td rowspan="3">No heating</td><td rowspan="3">No heating</td><td>20</td><td>20.97</td></tr>
<tr><td>Heating consumption (kWh)</td><td>691.4</td><td>549.33</td><td>756.59</td><td>451.55</td></tr>
<tr><td>Target indoor temperature (°C)</td><td>/</td><td>/</td><td>/</td><td>21</td></tr>
<tr><td>Household number</td><td>10301</td><td>10302</td><td>20301</td><td>20302</td><td>30301</td><td>30302</td><td>40301</td><td>40302</td></tr>
<tr><td>Indoor temperature (°C)</td><td rowspan="3">Non-heated</td><td>21.23</td><td>21.64</td><td>20.63</td><td>19.67</td><td rowspan="3">Heated</td><td>16.51</td><td>22.03</td></tr>
<tr><td>Heating consumption (kWh)</td><td>655.08</td><td>555.04</td><td>614.61</td><td>698.47</td><td>0</td><td>501.53</td></tr>
<tr><td>Target indoor temperature (°C)</td><td>21</td><td>/</td><td>/</td><td>/</td><td>/</td><td>/</td></tr>
<tr><td>Household number</td><td>10201</td><td>10202</td><td>20201</td><td>20202</td><td>30201</td><td>30202</td><td>40201</td><td>40202</td></tr>
<tr><td>Indoor temperature (°C)</td><td>18.63</td><td>23.08</td><td>21.94</td><td>22.32</td><td>16.98</td><td>19.99</td><td>19.44</td><td>23.1</td></tr>
<tr><td>Heating consumption (kWh)</td><td>631.55</td><td>644.67</td><td>603.21</td><td>484.78</td><td>0</td><td>744.85</td><td>659.59</td><td>699.98</td></tr>
<tr><td>Target indoor temperature (°C)</td><td>/</td><td>/</td><td>/</td><td>/</td><td>/</td><td>20</td><td>/</td><td>/</td></tr>
<tr><td>Household number</td><td>10101</td><td>10102</td><td>20101</td><td>20102</td><td>30101</td><td>30102</td><td>40101</td><td>40102</td></tr>
<tr><td>Indoor temperature (°C)</td><td>14.84</td><td>15.58</td><td>21</td><td>/</td><td>18.77</td><td>14.25</td><td>21.2</td><td>/</td></tr>
<tr><td>Heating consumption (kWh)</td><td>0</td><td>0</td><td>684.15</td><td>495.51</td><td>851.75</td><td>0</td><td>601.33</td><td>566.96</td></tr>
<tr><td>Target indoor temperature (°C)</td><td>/</td><td>/</td><td>/</td><td>/</td><td>/</td><td>/</td><td>/</td><td>/</td></tr>
</table>

Note. The "/" in indoor temperature column indicated that the indoor temperature has no value due to communication problems. The "/" in target indoor temperature column indicates the on-off valve was on always. The blue represents the outer households, and the light red and yellow are the inner households.

3.2. The Relationship between Indoor Temperatures in Different Locations

For a building, the indoor temperature of the object household was not only affected by the household situated above but also by the locations, e.g., the indoor temperature of inner households was higher than that of the households situated side, bottom, and top [36,37]. Table 2 shows the average indoor temperature and heating consumption of each household in Case 1 from 9 to 13 February. The blue represent the outer households, and the yellow are the inner households.

The k-means were adopted to cluster the indoor temperature of the inner and outer households, respectively. The variables include indoor temperature, household number, and heated or non-heated. The maximum silhouette value (0.76/0.78) was found when k = 3 for the inner and outer households, and an average silhouette value higher than 0.7 showed excellent separation between the clusters [38]. The classification results are shown in Tables 3 and 4.

Table 3. The classification results for inner households.

Household Number	Indoor Temperature (°C)	Category	Description
20501	20.33	Cluster 1	Target indoor temperature was 20 °C
20502	16.85	Cluster 2	Having non-heated household situated above
30501	21.69	Cluster 3	/
20401	21.95	Cluster 3	/
40401	20.00	Cluster 1	Target indoor temperature was 20 °C
10302	21.23	Cluster 3	/
20301	21.64	Cluster 3	/
20302	20.63	Cluster 1	Having non-heated household situated above
30301	19.67	Cluster 1	Having non-heated household situated above
10202	23.08	Cluster 3	/
20201	21.94	Cluster 3	/
20202	22.32	Cluster 3	/
30202	19.99	Cluster 1	Target indoor temperature was 20 °C
40201	19.44	Cluster 1	Having non-heated household situated above

Table 4. The classification results for outer households.

Household Number	Indoor Temperature (°C)	Category	Description
10602	18.94	Cluster 3	The household on the top floor
20601	19.19	Cluster 3	The household on the top floor
30601	18.82	Cluster 3	The household on the top floor
40502	22.20	Cluster 1	/
40402	20.97	Cluster 3	Target indoor temperature was 21 °C
40302	22.03	Cluster 1	/
40202	23.10	Cluster 1	/
40101	21.20	Cluster 1	/
30101	18.77	Cluster 3	Having non-heated household situated above
20101	21.00	Cluster 1	/
10201	18.63	Cluster 3	Having non-heated household situated above
10401	18.93	Cluster 3	The indoor temperature for the household situated above was low
10501	14.85	Cluster 2	Having non-heated household situated above

As shown in Table 3, the indoor temperatures in Cluster 1 and Cluster 2 were interfered with by the self-regulation behavior of the heat user and the non-heated household situated above, while, in Cluster 3, it was mainly determined using the heated parameters. Table 4 shows that three types were included for Cluster 2 and Cluster 3; the first type was low target indoor temperature, the second type was the non-heated household situated above, and the third type was the households on the top floor. Only indoor temperature in Cluster 1 was mainly determined using the heated parameters.

At present, many heat users do not have to regulate devices, and a few users have devices, but their self-regulating behaviors are weak. Therefore, the indoor temperature mainly depends on the heated parameters. In order to generalize the analysis results, Cluster 3 for inner households and Cluster 1 for outer households were selected for analysis. For outer/inner households, the average indoor temperature was 21.41 °C/21.97 °C, with a maximum value of 23.1 °C/23.08 °C, a minimum value of 21.2 °C/21.23 °C, and a difference of 1.9 °C/1.85 °C.

For the outer households, the indoor temperatures of 40202 households were the highest (23.1 °C), and those of 10501 households were the lowest (14.85 °C); the difference value was 8.25 °C, and the reason was that the household situated above 10601 was non-heated. The right side households, which were all heated, had higher average indoor temperature (22.1 °C) and lower heating consumption (541.9 kWh) than on the left side (17.47 °C/670.2 kWh). It noted that the non-heated household had a great impact on the household situated below, especially the household that had a large outer envelope structure on the top floor, i.e., the corner household on the top floor.

From the above analysis, the following conclusions can be preliminarily obtained:

(1) No matter the indoor temperature of the outer or inner households, which were mainly determined using the heated parameters, the temperature difference between the maximum and minimum value was about 2 °C;
(2) The average indoor temperature of the inner households was higher than that of the outer households;
(3) The indoor temperature of the household on the top floor was generally lower than that of the inner household;
(4) The corner non-heated households on the top floor had a greater impact on the households situated below than those on the other floors.

In order to further verify the universality of the above conclusions, the indoor temperature and heating consumption of households in Case 2–Case 6 from 1 to 5 February were analyzed. The indoor temperatures of the inner and outer households in each case were clustered, respectively, and the indoor temperatures of households, which were affected by the heated parameters, were selected for analysis. The results are shown in Table 5, and the analysis for outer households is shown in Table 6.

Table 5. The analysis results for conclusions 1 and 2.

Case		Case 2	Case 3	Case 4	Case 5	Case 6
Inner households	Number	8	16	80	48	24
	The maximum value (°C)	23.56	22.31	23.33	23.55	22.98
	The minimum value (°C)	21.88	20.85	20.61	21.61	20.54
	Difference value(°C)	1.68	1.46	2.72	1.91	2.44
	Average value (°C)	22.89	21.45	22.1 °C	22.67	21.41
Outer households	Number	16	20	40	32	32
	The maximum value (°C)	23.85	21.62	21.78	24.01	21.37
	The minimum value (°C)	21.85	19.7	20.07	21.96	19.62
	Difference value(°C)	2	1.92	1.71	2.06	1.75
	Average value (°C)	22.3	20.62	20.75	22.62	20.81

Table 6. The analysis results of conclusions 3 and 4.

Case		Case 2	Case 3	Case 4	Case 5	Case 6
The household on the top floor	Average indoor temperature (°C)	19.49	18.74	20.3	21.85	19.12
	Average heating consumption (kWh)	931.62	455.80	469.23	480.46	717.08
The household on the other floor	Average indoor temperature (°C)	22.48	20.64	20.92	22.16	20.23
	Average heating consumption (kWh)	596.30	438.91	444.11	397.12	609.83
The left corner household on top floor	Yes/No heated	Yes	No	Yes	No	No
	Average indoor temperature of the households situated below (°C)	21.85	18.2	18.36	19.15	16.47
	Average heating consumption of the households situated below (kWh)	543.43	571.78	0	451	594.36
The right corner household on the top floor	Yes/No heated	Yes	Yes	Yes	Yes	No
	Average indoor temperature of the households situated below (°C)	23.85	21.62	21.24	20.27	17.62
	Average heating consumption of the households situated below (kWh)	587.26	419.23	590.36	123.34	729.68

Table 5 showed that the average indoor temperature of the inner households was always higher than that of the outer households, which was consistent with conclusion 2. The temperature difference between the maximum and minimum values was basically within 2 °C. For Case 4, the inner household numbers were relatively dense, which was two times that of the outer. For Case 6, the occupancy rate was low, and the temperature difference increased, but it was still below 3 °C.

Table 6 showed that the average indoor temperature of the households on the top floor was lower than that of other floors, but the heating consumption was higher, which was consistent with conclusion 3. In Case 6, the corner household on the top floor was non-heated, so the indoor temperature of the household situated below was low and could not reach the target value. In Case 4, the left corner household on the top floor was heated, and the household situated below was non-heated, but the indoor temperature was high, which was 18.36 °C. Therefore, the heated or not corner household on the top floor had a serious impact on the households situated below.

4. Installation Principle and Calculation Model

4.1. Installation Principle

The above analysis showed that the indoor temperature of the household on the top floor was lower than that of the other floors, the average indoor temperature of the outer households was lower than that of the inner households, and the indoor temperature variation in the object household was greatly affected by the heated condition of the household situated above. Therefore, the indoor temperature of the households in large-scale buildings could be divided into three categories, as shown in Figure 3: the first category included top-floor households, the second category included inner households, and the third category included outer households, excluding households on the top floor.

Therefore, the following installation principles should be followed for the representative temperature-monitoring points: (1) at least one point in the first category; (2) at least one point that the household situated above was heated and one point that the household situated above was non-heated in the second /third category. So, at least five points should be installed to evaluate the heating requirement in large-scale buildings, i.e., the five-point method.

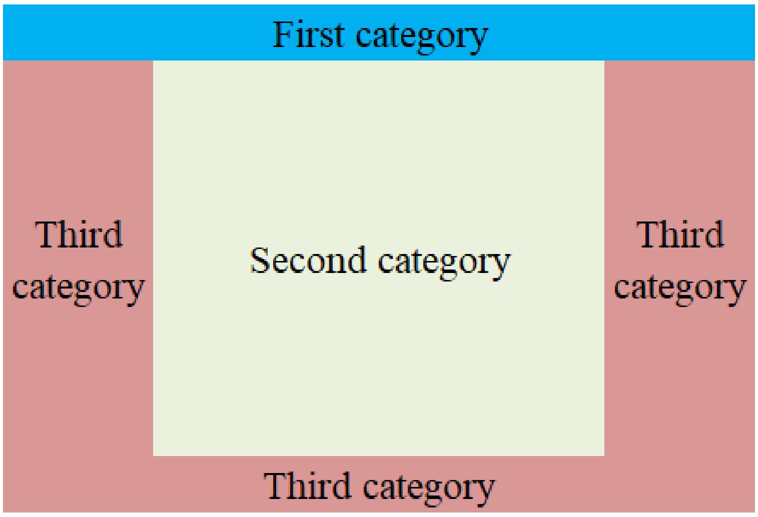


Figure 3. The indoor temperature categories in a building.

4.2. Calculation Model

After the installation principle was determined, it was important to determine the calculation proportion of each representative point. For the point in the first category, the proportion was one to the total number of floors. For the second and third categories, the proportion of the points, that had heated households situated above, could be obtained as follows: one non-heated household affected one object household, except the non-heated household on the first floor, so the proportion was the heated households to the total households after removing the households on the first floor, which was called the heat ratio on the middle floor (ζ), and the proportion for the points, which has non-heated households situated above, was $1-\zeta$. The comprehensive indoor temperature calculation model of large-scale buildings is shown in Equation (8).

$$\overline{T}_{in}^{model} = \frac{\eta * \frac{\sum_{u=1}^{i} T_{in}^{u}}{i} + \zeta * \frac{\sum_{n=1}^{j} T_{in}^{n}}{j} + (1-\zeta) * \frac{\sum_{h=1}^{k} T_{in}^{h}}{k}}{\eta + 1} \quad (8)$$

where η was the proportion of top floor households, $\eta = \frac{1}{N}$; N was the total floors; T_{in}^{u} was the indoor temperature of first category households, °C; T_{in}^{h} was the indoor temperature of second/third category households with heated household situated above, °C; T_{in}^{n} was the indoor temperature of the second/third category household with non-heated household situated above, °C; i was the number of temperature-monitoring points for the first category; j was the number of temperature-monitoring points for second/third category household with heated household situated above; k was the number of temperature-monitoring points for the second/third category household with non-heated household situated above.

The data in Case 2 from 1 to 7 February were used to verify the validity of the model, ζ = 0.85. In Table 7, the hourly average indoor temperature of 19 heated households was represented as $\overline{T}_{in}^{actual}$, which could reflect the real heating requirement. So, the closer the $\overline{T}_{in}^{model}$ or the traditional average method ($\overline{T}_{in}^{avg}$) was to $\overline{T}_{in}^{actual}$, the better the calculation method was. Different scenarios were constructed: Scenario 2 adopted the five-point method to choose the representative points, and Scenario 3 and Scenario 4 selected the representative points randomly. The comparison results of the different calculation methods for different scenarios are shown in Figures 4–7.

Table 7. Layout of each heat user in Case 2.

10601 (Scenario 3)	10602 (Scenario 1)	20601 (Scenario 1,2, 4)	20602 Scenario (1,3,4)
10501 (Scenario 1)	+10502 (Scenario 1)	20501 (Scenario 1)	20502 (Scenario 1,3)
10401 (Scenario 1)	10402 (Scenario 1,2)	20401 (Scenario 1, 2, 3)	20402 (Scenario 1)
10301 (Scenario 1)	10302 (Scenario 1, 2, 3, 4)	20301 (Scenario 1)	20302 (Scenario 1)
10201(Scenario 1)	+10202 (Scenario 1)	+20201 (Scenario 1)	20202 (Scenario 1,4)
10101 (Scenario 1, 2)	10102 (Scenario 1,4)	+20101 (Scenario 1)	+20102 (Scenario 1)

Note. + represented non-heated households.

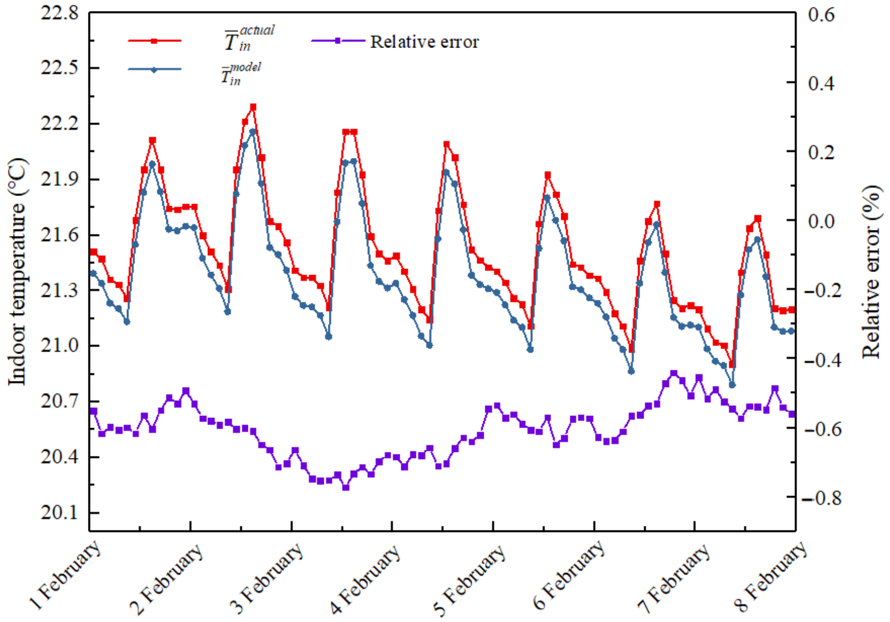


Figure 4. Comparison of $\overline{T}_{in}^{actual}$ and $\overline{T}_{in}^{model}$ for Scenario 1.

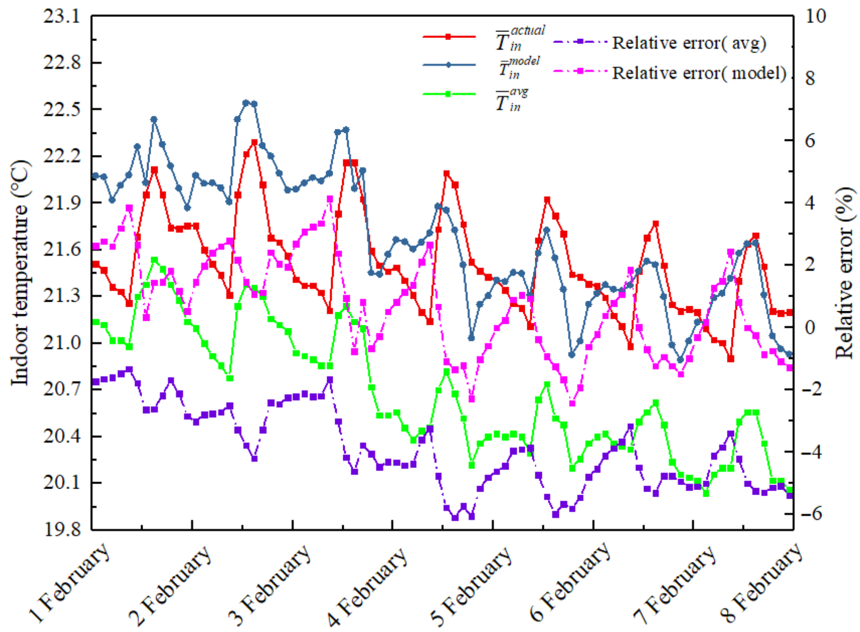


Figure 5. Comparison of $\overline{T}_{in}^{actual}$, $\overline{T}_{in}^{avg}$, and $\overline{T}_{in}^{model}$ for Scenario 2.

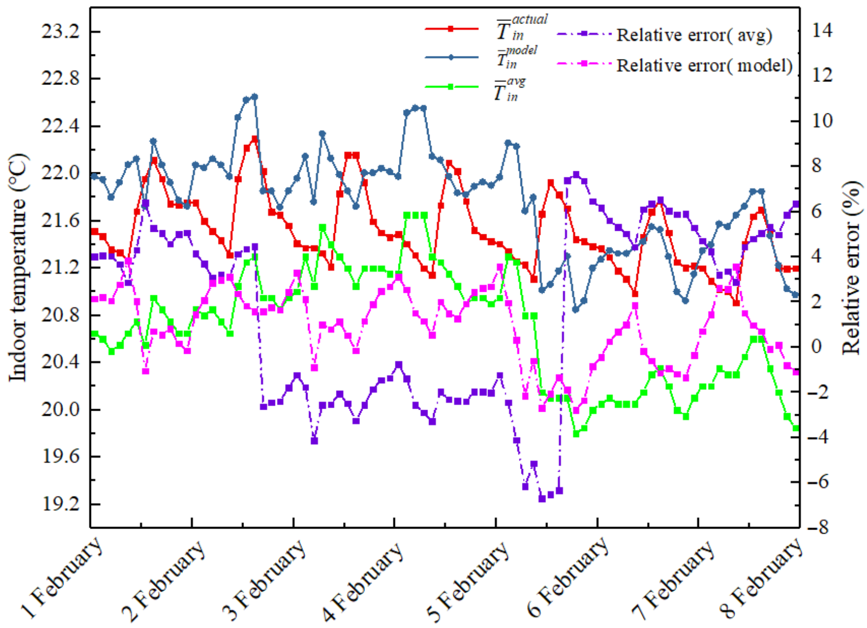


Figure 6. Comparison of $\overline{T}_{in}^{actual}$, $\overline{T}_{in}^{avg}$, and $\overline{T}_{in}^{model}$ for Scenario 3.

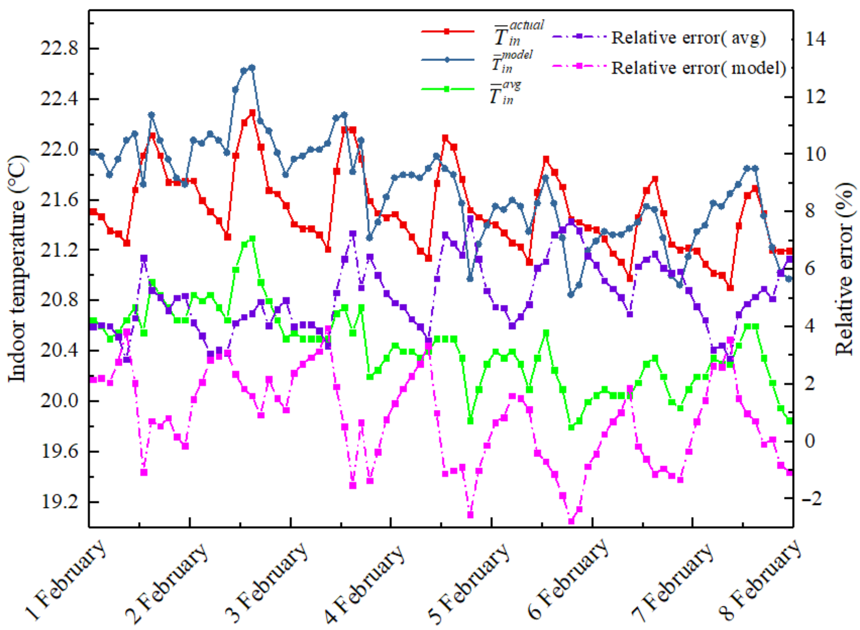


Figure 7. Comparison of $\overline{T}_{in}^{actual}$, $\overline{T}_{in}^{avg}$ and $\overline{T}_{in}^{model}$ for Scenario 4.

Figure 4 showed that the variation trends of $\overline{T}_{in}^{actual}$ and $\overline{T}_{in}^{model}$ were basically the same: the maximum error was 0.77%, the minimum error was 0.44%, and the average error was 0.6%, indicating that when all heated users installed the temperature-monitoring device, the comprehensive indoor temperature calculated via Equation (8) could represent the actual average temperature of the building.

When representative temperature-monitoring points were installed according to the five-point method, as shown in Figure 4, for the traditional average method, the maximum error between $\overline{T}_{in}^{avg}$ and $\overline{T}_{in}^{actual}$ was 6.09%, the minimum value was 1.32%, and the average value was 3.87%. For the model method, the maximum error between $\overline{T}_{in}^{model}$ and $\overline{T}_{in}^{actual}$ was 4.41%, the minimum error was 0.003%, and the average error was 1.44%. The above indicated that $\overline{T}_{in}^{model}$ was more consistent with $\overline{T}_{in}^{actual}$, i.e., $\overline{T}_{in}^{model}$ can reflect the actual heating requirement, and the installation principle of the five-point method was right.

When the representative temperature-monitoring points were installed randomly, Figure 6 showed that the maximum error between $\overline{T}_{in}^{avg}$ and $\overline{T}_{in}^{actual}$ was 7.76%, the minimum value was 2.87%, the average value was 5.07%, the maximum error between $\overline{T}_{in}^{model}$ and $\overline{T}_{in}^{actual}$ was 3.95%, the minimum error was 0.09%, and the average error was 1.50%. It could be concluded that the installation principle of the representative points did not satisfy the five-point method. The error of the calculated comprehensive indoor temperature was larger than that of the actual value, and the obtained comprehensive indoor temperature using the model method was still much closer to the actual value.

Figure 7 showed that the maximum error between $\overline{T}_{in}^{avg}$ and $\overline{T}_{in}^{actual}$ was 10.87%, the minimum value was 0.76%, and the average value was 5.81%. The maximum error between $\overline{T}_{in}^{model}$ and $\overline{T}_{in}^{actual}$ was 5.62%, the minimum error was 0.03%, and the average error was 2.32%.

The above analysis obtained that the accuracy of the proposed $\overline{T}_{in}^{model}$ was high for all scenarios, and when the representative points were installed according to the five-point method, i.e., Scenario 1, the $\overline{T}_{in}^{model}$ was closest to $\overline{T}_{in}^{actual}$ with the smallest error.

5. Application

Section 4 verified the correctness of the five-point installation principle and the accuracy of the comprehensive indoor temperature calculation model. This section would analyze the representative temperature-monitoring points, which had been installed randomly to truly evaluate the heating requirement.

A heating substation in Tianjin was selected, which served a large number of residential buildings with high floors. The highest building had 18 floors, and the high and low zones were divided to ensure the safe and stable operation of the heating system, so the above 13 floors belonged to the high zone, including 13 floors, and the below 13 floors belonged to the low zone. The difference in occupancy rate for the high zone and low zone was small. Due to the poor communication signal in the high zone, not all temperature-monitoring data could be collected. In December, the supply and return temperatures in high and low zones were basically the same, i.e., the difference in comprehensive indoor temperature was not large. It was not known whether the household situated above for the representative temperature-monitoring points was heated or not, so the conclusion in Section 3.2 was used to categorize, i.e., no matter the outer or inner households, which had heated household situated above, the temperature difference between the maximum and the minimum value was about 2 °C, within 2 °C was T_{in}^{n}, exceeding 2 °C was T_{in}^{h}. The categorization results are shown in Table 8, and the temperature for each representative monitoring point was the average value from 18 to 20 December.

ζ = 0.5 was used to compare the comprehensive indoor temperature of the high and low zones. The simplified calculation method is shown in Equation (9). In practical application, the installation principle and calculation model should be carried out according to Section 4. For the high zone and low zone, the calculation results of comprehensive indoor temperature using the model method and average method are shown in Figure 8.

$$\overline{T}_{in}^{model} = 0.5 * \frac{\sum_{n=1}^{j} T_{in}^{n}}{j} + 0.5 * \frac{\sum_{h=1}^{k} T_{in}^{h}}{k} \tag{9}$$

Table 8. The result of categorization.

Building Number	High Zone		Low Zone	
	Second Category	Third Category	Second Category	Third Category
5#				*24.21, *24.92
6#			*22.22	*25.6, *23.4
7#			#21.3	*22.53
8#				*22.8, *23.11
9#			#22.2	
10#	*24.42		*22.8	
11#	#21.1		*24.9	
12#	*22.73		*23.24	
13#			*22.9, *22.77, *24.8	
14#			*23.9, *24.09	*21.89
15#	#20.65, *24.05		*22.1, *24.8	
16#			*25.26	#21.62, #20.57
17#	*26.52		*23.23, *24.3	*23.62

Note. */# represented T_{in}^{n}/T_{in}^{h} for high zone and low zone.

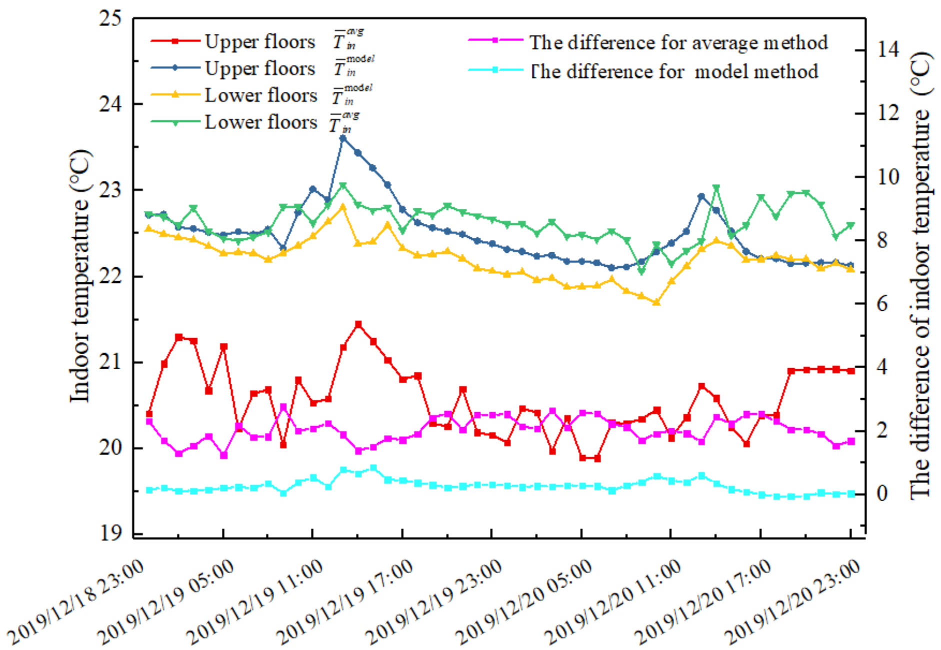


Figure 8. Comparison of $\overline{T}_{in}^{avg}$ and $\overline{T}_{in}^{model}$ in high/low zones.

Figure 8 showed that the red line was far away from the green line, meaning that the comprehensive indoor temperature calculated using the average method, had a big gap between the high zone and low zone. The average temperature difference was 2.06 °C, the maximum value was 2.77 °C, and the minimum value was 1.25 °C. If the staff adjusted the heated parameters based on this value, that would lead to high indoor temperatures and excessive heating consumption in high zones. The difference in comprehensive indoor temperature between the high and low zones calculated using the model method was relatively small, with an average value of 0.28 °C, a maximum value of 0.86 °C, and a minimum value of 0.05 °C. Although the representative temperature-monitoring points were installed randomly, the heated condition of the household situated above the installation points was unknown, and the occupancy rate was not obtained. Compared with the traditional average method, the comprehensive indoor temperature calculated using the model method can well evaluate the heating requirement of high zone and low zone.

In addition, the instability of communication would lead to the discontinuity of temperature-monitoring data transmission. Taking the high zone as an example, some temperature-monitoring data were removed at a certain time to illustrate the influence of instability of communication on the hourly comprehensive indoor temperature obtained using different calculation methods. The formulas of hourly indoor temperature difference were shown in Equations (10) and (11). The comparison results are shown in Figure 9.

$$\Delta\overline{T}_{in}^{avg} = \overline{T}_{in}^{avg^i} - \overline{T}_{in}^{avg^{i-1}} \tag{10}$$

where $\Delta\overline{T}_{in}^{avg}$ was the difference in hourly indoor temperature (°C); $\overline{T}_{in}^{avg^i}$ was the comprehensive indoor temperature of the building at ith (°C); and $\overline{T}_{in}^{avg^{i-1}}$ was the comprehensive indoor temperature of the building at $i-1$st for the average method (°C).

$$\Delta\overline{T}_{in}^{model} = \overline{T}_{in}^{model^i} - \overline{T}_{in}^{model^{i-1}} \tag{11}$$

where $\Delta\overline{T}_{in}^{model}$ was the difference in hourly indoor temperature (°C); $\overline{T}_{in}^{model^i}$ was the comprehensive indoor temperature of the building at ith (°C); and $\overline{T}_{in}^{model^{i-1}}$ was the comprehensive indoor temperature of the building at $i-1$st for the model method (°C).

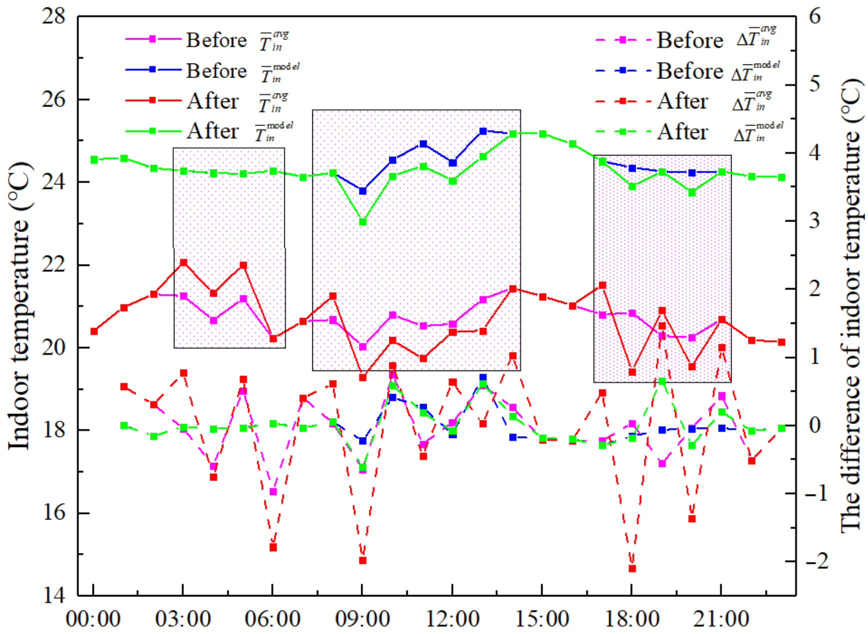


Figure 9. Comparison of $\overline{T}_{in}^{avg}$ and $\overline{T}_{in}^{model}$ in the high zone with instability of communication.

Figure 9 showed that the difference in the hourly indoor temperature for the average method was large, the maximum $\left|\Delta\overline{T}_{in}^{avg}\right|$ was 2.08 °C, and the average $\left|\Delta\overline{T}_{in}^{avg}\right|$ was 1.01 °C, which was not possible in normal continuous heating. For the model method, the $\left|\Delta\overline{T}_{in}^{model}\right|$ was small, the maximum $\left|\Delta\overline{T}_{in}^{model}\right|$ was 0.6 °C, and the average $\left|\Delta\overline{T}_{in}^{modell}\right|$ was 0.26 °C. It could be concluded that the comprehensive indoor temperature calculated using the model method was less affected by the instability of communication.

6. Conclusions

The indoor temperature was an important criterion to judge whether the heating system achieved on-demand heating. However, for large-scale buildings, it was impossible to install temperature-monitoring devices in every household but possible to install them at some representative locations. Where was the representative location? How much do we install? How do we calculate the collected indoor temperature to obtain the comprehensive indoor temperature? This paper conducted relevant research and drew the following conclusions and suggestions:

(1) Compared with households situated below, left, and right, the indoor temperature variation in households situated above had the greatest correlation with that of the object household, which provided a new energy-saving regulation strategy.
(2) The average indoor temperature of inner households was higher than that of outer households, and the indoor temperature of households on the top floor was generally lower than that of other floors.
(3) The corner non-heated households on the top floor had a greater impact on the household situated below than those on the other floors, whether the two households were heated or not. It was recommended to open the valves.
(4) Compared with the traditional method, the comprehensive indoor temperature obtained using the installation principle and calculation model was closer to the actual value and was less affected by the instability of communication.

In summary, the proposed installation principle and calculation model could help heating company staff truly understand the heating requirement and make accurate energy-saving control strategies.

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