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Assessment of Summer Overheating in Concrete Block and Cross Laminated Timber Office Buildings in the Severe Cold and Cold Regions of China

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Abstract: The aims of the paper were to clarify whether office buildings in the severe cold and cold regions are overheating, especially those with natural ventilation, and whether potential overheating is related to the building materials. The severe cold and cold regions of China were considered to be cool regions during summer. However, with global warming, improvements in the thermal performance of the building envelope and the urban heat island effect, office buildings in these regions are showing different degrees of overheating during summer. Two office building materials commonly used in this area, cross laminated timber (CLT) and concrete block, were simulated in this study. With reference to the overheating standard, the degree of overheating in six cities in the severe cold and cold regions was quantitatively analysed and the extent of overheating for the two building materials was compared. Finally, the influence of thermal insulation on building overheating is discussed, and some suggestions are put forward to improve the relevant national regulations in China. The results show that office buildings in the severe cold and cold regions experience overheating during summer, and CLT buildings are more prone to overheating than concrete buildings during summer. This is attributable to the different thermal mass of the materials. Thick insulation does increase the risk of building overheating, and the effect on concrete buildings is more pronounced. Concrete buildings with an insulation layer can experience overheating for 27–71 h more than buildings without an insulation layer. Insulation on CLT buildings only results in an increase of 11–37 h. When considering the current situation with summer overheating in the severe cold and cold regions, relevant codes should also be modified and improved accordingly to guide building design, so as to achieve low-carbon and energy-saving goals.

Keywords: office building; summer overheating; severe cold regions; cross laminated timber (CLT)

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1. Introduction

1.1. Overheating Phenomenon

1.1.1. Global Climate Change and the Urban Heat Island Effect

In recent decades, the impact of global warming on overheating risk has demanded increased attention, even for high-latitude areas [1–3]. Instead of being an issue of extreme peaks in a single day, the tendency is for high temperatures to last over longer durations [4]. According to NASA, the average global temperature in 2020 was 1.02 °C higher than the baseline average from 1951 to 1980 [5]. Since the late 19th century, the Earth's average temperature has risen by over 1.2 °C [5]. In China, there are five major architectural climate regions, among which two are the severe cold and cold regions. As shown in Figure 1, the representative cities for these two regions are Hailar (severe cold 1A), Harbin (severe cold 1B), Changchun and Shenyang (1C), Dalian (cold 2A) and Beijing (cold 2B) [6]. These areas used to be considered as cool during summer. Recent studies have estimated that the temperature in Harbin and Beijing will increase by 5.5 and 2.7 °C, respectively, by 2100 [7]. As the climate changes, the performance of buildings will also change. It was found that cooling energy consumption in office buildings does increase with global warming [8–11]. Cooling energy consumption is expected to increase in all five areas, with an increase of 18.5% in Harbin and 20.4% in Beijing [12]. Hence, the severe cold and cold regions also face the problem of overheating. According to related studies, cooling energy use intensity will increase on average by 15–126% by 2070, depending on the baseline climate and building typology [13]. In addition, the urban heat island effect may result in city temperatures being as much as 9 °C higher than in surrounding rural areas, which exacerbates building overheating in cities [14].

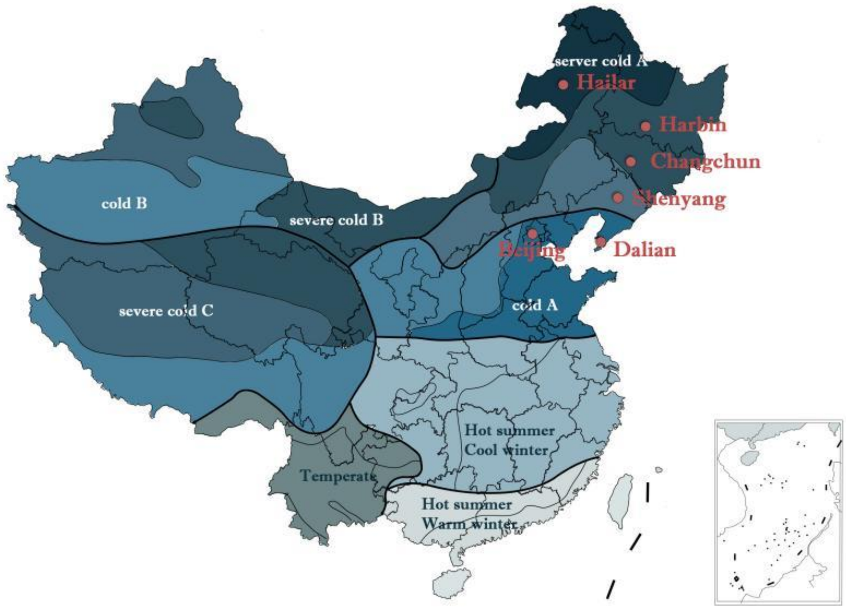


Figure 1. Location of the six case study cities in mainland China. (Source: Standard for building climate zoning GB 50178-93; drawn by the authors).

1.1.2. Public Buildings

In the past, office buildings in the severe cold and cold regions of China were considered not to experience overheating problems. However, recent studies have highlighted the phenomenon of increased overheating risk in public buildings in these areas, especially in buildings without air-conditioning [15–17]. In the UK, several buildings, especially naturally ventilated office buildings, already perform poorly under hot weather conditions [18]. In 2016, 65% of office buildings were air-conditioned in the UK, compared to 10% at the end of 1944 [19,20]. Recent studies have shown that, due to the type and design of these buildings, up to 90% of hospital wards (by floor area) are vulnerable to overheating during periods of high temperature in England. Other buildings such as schools and prisons are also at increased risk of overheating during summer in England [21]. A Dutch study showed that peak cooling loads in office buildings are expected to increase by 70% during the 30-year period 2008–2038 in order to maintain thermal comfort [22]. In the severe cold and cold regions, the building envelope is usually well insulated in order to reduce the heating energy demand during winter. This insulation increases the risk of overheating during summer [16,23–25].

1.1.3. Disadvantages of Overheated Buildings

Over 50% of the world's population now works in offices. Indoor temperature and lighting are the most important factors affecting the performance of office workers. The metabolism of the office staff together with heat dissipation from office lighting and office equipment increase the internal heat of office buildings. With climate change and the intensification of the urban heat island effect, office buildings are particularly vulnerable to overheating [26]. Elevated air temperatures can result in thermal discomfort and this has a negative impact on work efficiency [27–29]. At the same time, it has been shown that when the indoor temperature exceeds a certain value, the work performance generally decreases. Studies have shown that when the temperature exceeds 25 °C, the work performance decreases by 2% on average for every 1 °C increase in temperature [30]. Furthermore, increasing temperatures can increase the risk of heart or respiratory disease, and in extreme cases, can cause death [31–33].

1.2. Global Overheating Standards

Although overheating is a critical factor for occupant comfort in office buildings, there is no consistent standard defining overheating. Different countries and regions have different standards. Examples include the CIBSE Guide A and TM52 in the UK, the Standard Effective Temperature in the US and GB/T 50785-2012, JGJ/T 67-2019 and GB 50736-2012 in China. These standards, some specific to office buildings and some general, all describe how to assess overheating or indoor thermal comfort during summer.

In the UK, the Chartered Institution of Building Services Engineers (CIBSEs) developed several best practice guides for summer overheating in offices (Figure 2). These criteria are used for assessing buildings with natural ventilation. The CIBSE Guide A recommends that indoor operative temperatures during summer (from 1st May to 30th September) during occupied hours should not exceed 25 °C (typically 125 h). It also recommends that no more than 1% (typically 25 h) of annual occupied hours should have an operative temperature exceeding 28 °C during summer [34]. These criteria are static and ignore the impact of the adaptation of building occupants to warm climates [23]. They do not take into account the extent of overheating as well as its duration [35]. Recently, CIBSE updated the criteria in the CIBSE TM 52 guide to include adaptive thermal comfort. It established three criteria for overheating [35] (Table 1).

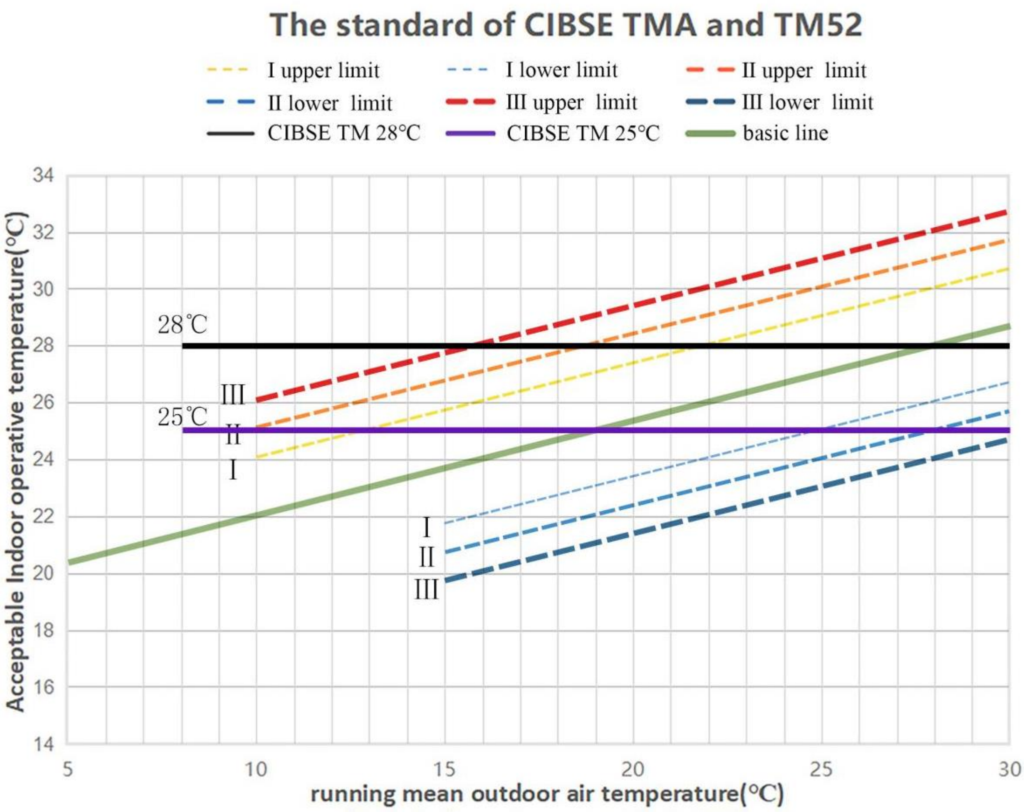


Figure 2. The standard of CIBSE TMA and TM52.

Table 1. Three criteria for overheating from CIBSE TM52.

Criteria	Content
Criteria 1	This displays the percentage hours when the difference in operative temperature minus the maximum acceptable temperature is greater than or equal to 1 K.
Criteria 2	This displays the maximum daily degree hours found for the space. This fails if it is greater than 6 K/h per day.
Criteria 3	This displays the maximum ΔT for the space. This space fails if it is greater than or equal to 4 K.

The maximum acceptable temperature (T_{max}) is calculated according to the criteria (Table 1 and Figure 2). There are three categories in total as shown in Table 2. CIBSE recommends that designers should aim to remain within Category II limits. For TM52, Category II should be used. This means that [36]:

$$T_{max} = 0.33T_{rm} + 21.8\ (^{\circ}C)$$

Table 2. Categories of building in CIBSE TM52.

Category	Explanation	Suggested Acceptable Range (K)
I	High level of expectation only used for the spaces occupied by very sensitive and fragile persons.	2
II	Normal expectation (for new buildings and renovations).	3
III	A moderate expectation (used for existing buildings).	4

In the formula, T_{rm} means the exponentially weighted running mean of the daily mean outdoor air temperature.

It should be noted that a building or a zone that does not satisfy any two of the three criteria is considered to be overheating. CIBSE TM52 evaluates not only indoor temperature, but also wind speed, the duration of overheating, human activity and other parameters related to thermal comfort. Therefore, it offers a more comprehensive assessment of overheating in naturally ventilated buildings.

In America, ASHRAE proposes an overheating criterion using the standard effective temperature (SET) to define the "liveable temperatures". It requires building simulation to demonstrate that a building's interior environment maintains "liveable temperatures" during a power outage that lasts seven days during the peak summertime of a typical year. For non-residential buildings, in the summertime, the SET should not exceed 86 °F (30 °C) for more than 18 SET °F degree-days (432 °F·h; or 240 K·h) during a one week period [23,37].

In China, the standards for the design of office buildings stipulate the indoor temperature of office buildings. Among the requirements, Class I and Class II office buildings should maintain a summer temperature of 24–26 °C, and the indoor wind speed should be less than or equal to 0.25 m/s. Class III office buildings have a summer temperature range of 26–28 °C and indoor wind speed should be less than or equal to 0.30 m/s [38].

According to the thermal comfort, two heating ventilation and air conditioning levels are set for buildings in the local design code. In the regulation for buildings level 1, comfortable temperature ranges from 24 to 26 °C. Similarly, for building level 2, comfortable temperature ranges from approximately 26 to 28 °C [39].

1.3. Building Materials

In severe cold and cold regions, building overheating during summer is not only a consequence of climate change and the thermal response of the construction materials, but it is also related to the high thermal insulation of the structure. It was found that the high insulation and low-U value can exacerbate the effects of building materials on overheating [40–42], especially for low thermal mass materials [43–45]. In these regions, concrete block and CLT are common building envelope materials. CLT, due to its green credentials and minimal environmental impact, has become widely used in office buildings in recent years. However, it has been shown that CLT has a higher risk of overheating than conventional high thermal mass materials [44,46].

Studies have also found that, in addition to the thermal mass of the envelope material, the thermal effusivity and thermal inertia of the material also have a bearing on building overheating. If the thermal capacity of the envelope remains the same while the temperature fluctuation range of the inner wall varies, this is due to the thermal effusivity of the material. It is important that the building envelope should have high thermal capacity as well as high thermal effusivity [44].

1.4. Study Objective

The phenomenon of office building overheating in cold regions at high latitudes is related to climate change and improved insulation measures in these areas. There are already several criteria for evaluating summer overheating, including the static approach in CIBSE Guide A, and the dynamic evaluation criterion defined in CIBSE TM52. These are used to assess overheating in naturally ventilated buildings during the summer occupancy period. Building overheating is related to thermal mass as well as the thermal effusivity and thermal inertia of the building envelope. High thermal mass and thermal efficiency are important for indoor thermal comfort, especially in buildings without air conditioning. Most existing studies focus on Europe, the United States and Canada, and there is no relevant study of the summer overheating of office buildings in the severe cold and cold regions in China. The problem of overheating in these regions has not been given any importance, and the relevant Chinese codes and standards do not consider the overheating problem during summer. Hence, office buildings in this area have not benefited from architectural design strategies to solve the problem. This has a detrimental effect on comfort in the building, reduces building performance and also consumes more energy [47]. Therefore, it is important to research overheating in office buildings in severe cold and cold areas.

This paper considers the potential risk of overheating during summer for concrete block, and CLT office buildings and addresses the following questions:

(1) Do office buildings in the severe cold and cold regions in China overheat during summer, particularly those with natural ventilation?

(2) Do regulations for the severe cold and cold regions need be adjusted?

(3) Is potential overheating is related to building materials?

The main purpose of this study was to determine whether office buildings in the severe cold and cold regions are overheating, especially those with natural ventilation. On this basis, this study proposes the relevant revision of Chinese codes and standards to correspond to cope with the changing environment. It concludes with an evaluation of overheating with different envelope materials, making comparisons to identify the underlying causes, in order to propose guiding strategies for future architectural design.

2. Methods and Data

2.1. Thermal Comfort

The term "thermal comfort" refers to that condition of mind that expresses satisfaction with the thermal environment. This is assessed by subjective evaluation. The main parameters that impact thermal comfort are temperature, thermal radiation, humidity and air speed; and the personal parameters are activity and clothing [48]. Air temperature is considered to be among the most critical parameters affecting thermal comfort. However, other factors should also be taken into account [49,50].

2.2. Definition of Overheating

The term "overheating" refers to the discomfort experienced by occupants caused by the accumulation of warmth within a building [51]. An overheating event is defined as successive and continuous indoor heat events that occur over a minimum of a set number of occupied hours which trigger physiological responses among the building occupants under these exposure conditions, and thus necessitate actions to restore thermal comfort [23].

2.3. Framework of the Study

The simulation considers the indoor air temperature and internal surface temperature of a wall in an office building without air-conditioning during summer. This study also examines the overheating properties of two different building materials. This study is divided into the following steps, as outlined in Figure 3. Six representative cities are selected from the severe cold areas (1A, 1B, 1C) and cold areas (2A, 2B) as the simulation environment. Shenyang and Changchun are two capital cities of Liaoning and Jilin province in China, which are both located in severe cold region (1C). As a result, both cities are selected for simulation. A 13-story concrete brick office building with 300 office units constructed in Harbin city is defined as the case study building. The summer conditions in this office building without air-conditioning are simulated using the commercial software IESVE. IESVE is a building performance simulation and analysis software which is provided by a UK company. It provides integrated analysis solutions for architects, engineers, consultants and other aspects of building performance, such as the model, energy consumption, air-conditioning system, natural ventilation, sunshine, lighting, CFD, cost, piping calculation, evacuation, LEED and BREEAM certification [52].

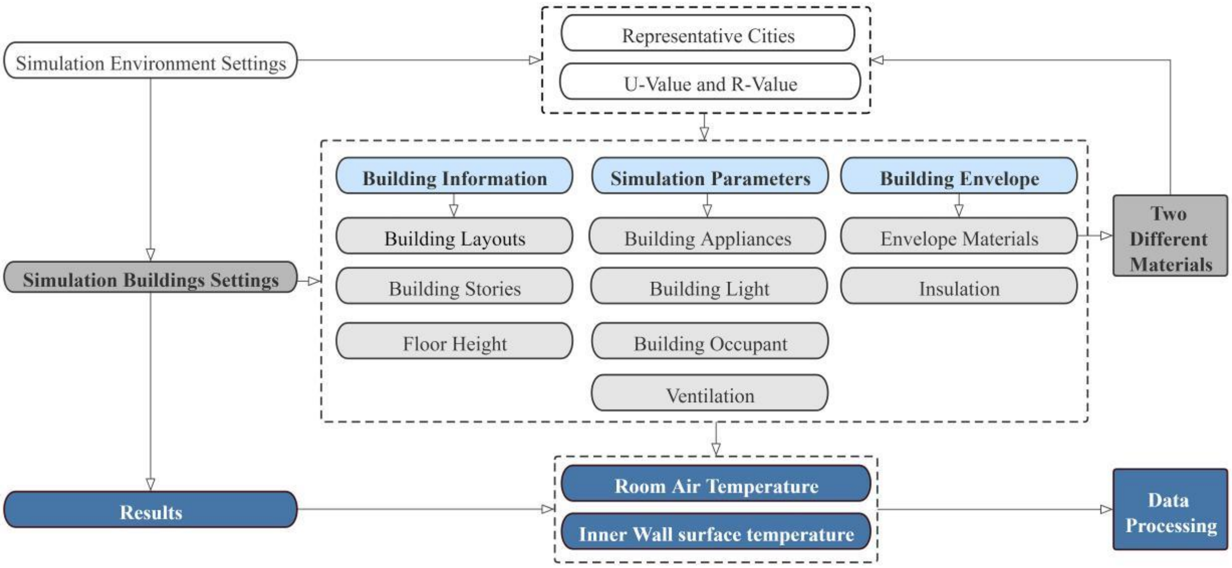


Figure 3. Flowchart for the building simulation.

During the simulation process, the following factors are examined as key parameters:

(1) Indoor air temperature;

(2) The inner surface temperature of the wall. The thermal response for concrete brick and CLT buildings is simulated and compared during the simulation (Figure 4).

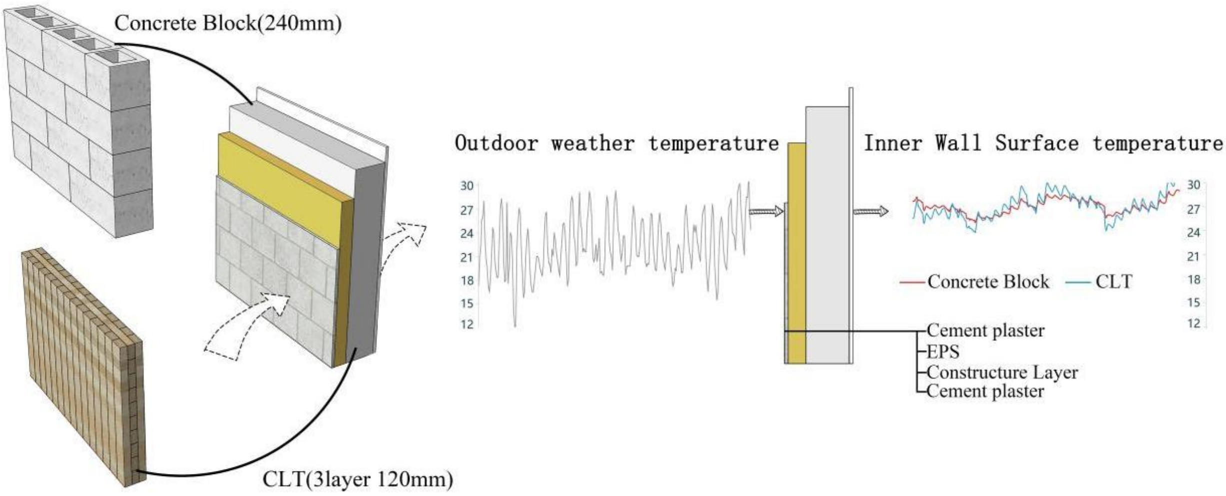


Figure 4. Schematic diagram of building structure simulation.

2.4. Simulation Environment

In order to evaluate the degree of overheating in office buildings without air-conditioning in the severe cold and cold regions, six typical cities from these regions were selected. These cities are Hailar, Harbin, Changchun, Shenyang, Dalian and Beijing. The U-value and R-value of the roof, walls, windows and ground were strictly defined to correspond to the relevant national norms and standards to ensure a realistic foundation for this study. The locations and the thermal design details for the case study building in the six cities are presented in Table 3.

Table 3. Case study parameters for severe cold and cold climate regions in China.

Climate Region	Sub-Region	Main Indicators		Representative City	U-Value (W/m^2·K)	R-Value (m^2·K/W)
		Temperature (°C)	HDD/CDD			
Severe cold	Severe cold 1A	$T_{min\cdot m} \leq -10$ °C $145 \leq d_{\leq 5}$	6000 ≤ HDD18	Hailar	Roof: ≤0.28 Wall: ≤0.38 Window: ≤2.2	Ground Floor: ≥1.10
	Severe cold 1B		5000 ≤ HDD18 < 6000	Harbin	Roof: ≤0.28 Wall: ≤0.38 Window: ≤2.2	Ground Floor: ≥1.10
	Severe cold 1C		3800 ≤ HDD18 < 5000	Shenyang; Changchun	Roof: ≤0.35 Wall: ≤0.43 Window: ≤2.3	Ground Floor: ≥1.10
Cold	Cold 2A	-10 °C < $T_{min\cdot m}$ ≤ 0 °C $90 \leq d_{\leq 5} < 145$	2000 ≤ HDD18 < 3800 CDD26 ≤ 90	Dalian	Roof: ≤0.45 Wall: ≤0.50 Window: ≤2.4	Ground Floor: ≥0.6
	Cold 2B		2000 ≤ HDD18 < 3800 CDD26 > 90	Beijing	Roof: ≤0.45 Wall: ≤0.50 Window: ≤2.4	Ground Floor: ≥0.6

Data Source: Design standard for energy efficiency of public buildings—CDD26: air condition degree days based on 26 °C; HDD18: heating degree days based on 18 °C; $d_{\leq 5}$: days of daily average temperature ≤5 °C; $T_{min\cdot m}$: average temperature of the coldest month.

In the table, the thermal transmittance (also known as U-value) is the rate of transfer of heat through a structure (which can be a single material or a composite), divided by the difference in temperature across that structure [53]. The R-value is a measure of how well a two-dimensional barrier, such as a layer of insulation, a window or a complete wall or ceiling, resists the conductive flow of heat. R-value is the temperature difference per unit of heat flux needed to sustain one unit of heat flux between the warmer surface and colder surface of a barrier under steady-state conditions [54]. The relationship between the U value and R value is presented as follows [55]:

$$U = 1/Rt$$

U is thermal transmittance.
Rt is the total thermal resistance of all materials.

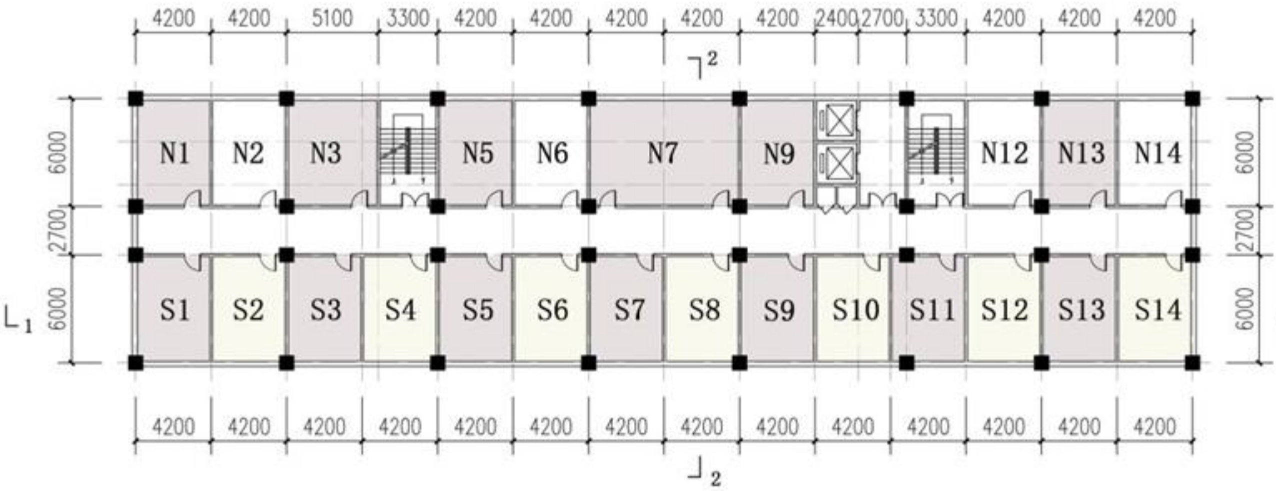
$$Rt = Rsi + R1 + R2 + R3 \ldots + Rn + Rse.$$

Rsi means interior surface thermal resistance (according to the norm by climatic zone).
Rse means exterior surface thermal resistance (according to the norm by climatic zone).

In the building code, heating degree day (HDD) and cooling degree day (CDD) are quantitative indices demonstrated to reflect demand for energy to heat or cool buildings.

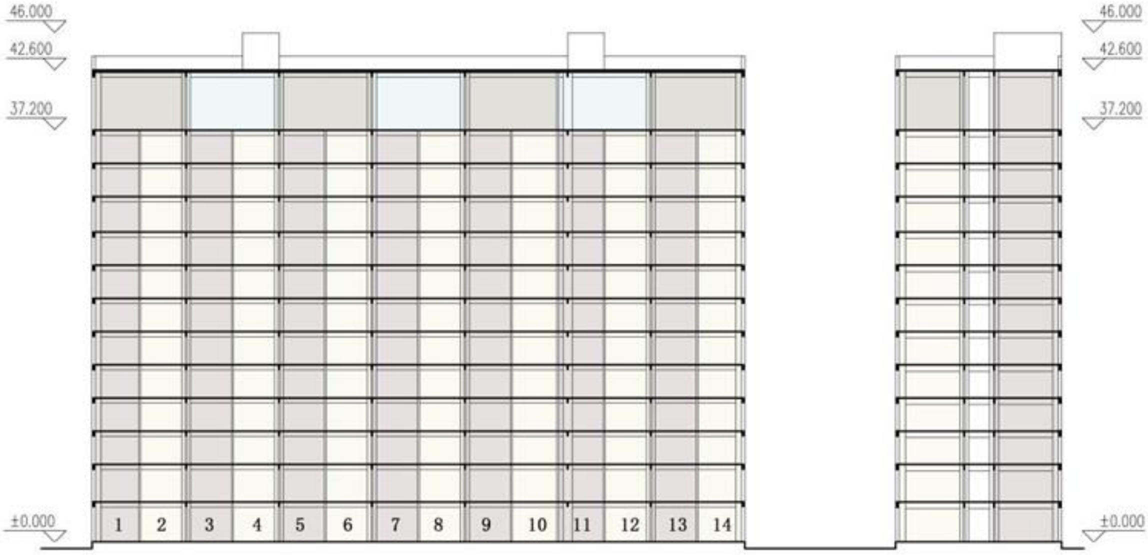
2.5. Details of the Simulation Building

The 13-story concrete brick building in Harbin chosen as the case study building is a typical design in the severe cold and cold regions. There are 24 units on each floor, with the floors from four to twelve as the standard layout. Two different building envelope structures are simulated in the six cities, with the principal components of the envelope structure in concrete brick and CLT. The concrete brick buildings use reinforced concrete for internal floors, and concrete brick for internal partitions. CLT is the main material for the internal floors and partitions in the CLT buildings. In the different cities, according to the relevant norms and climate characteristics, different thicknesses of insulation are applied. The details of the architectural design are presented in Figure 5 and Tables 4–6. The parameters of the three materials are shown in Table 7. The various building materials are defined in terms of their conductivity, density and specific heat capacity.



(**a**) Standard floor plan of the office building

Figure 5. *Cont.*



(**b**) 1–1 and 2–2 sections of the office building

Figure 5. Details of the architectural design.

Table 4. Building information.

Items	Values
Building function	Office, meeting
Total floor area	13 F
Number of rooms	300 (office, meeting) 28 (circulation)
Standard layer height	3.0 m
Window to wall ratio	0.34 (south) 0.28 (north)
Standard floor area	894 m^2
Openable windows rate	39%
Windowsill height	0.9
Window size	1.8 × 2.1 m (south) 1.8 × 1.8 m (north, east and west)

Table 5. Details of roof, external wall, and ground design.

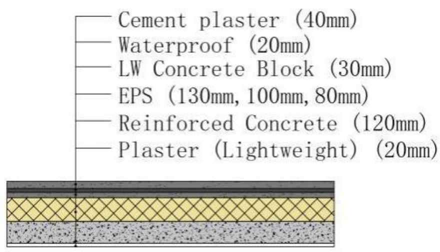
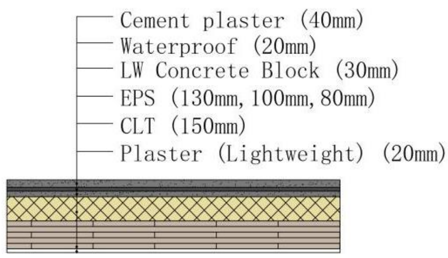
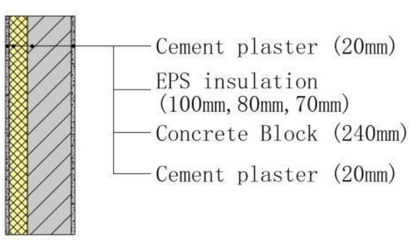
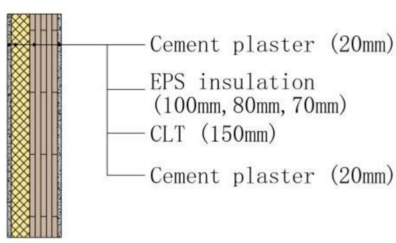
	Concrete	CLT
Roof		
Wall		

Table 5. *Cont.*

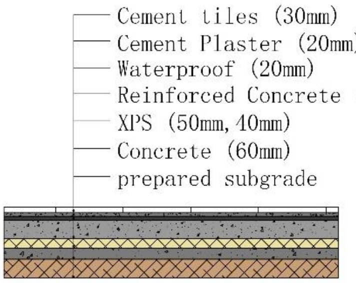
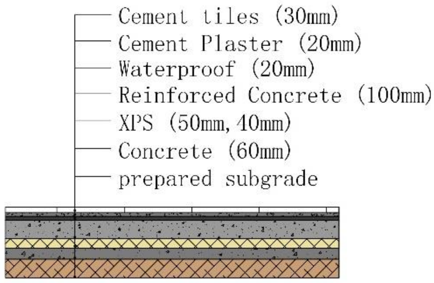
	Concrete	CLT
Ground		
Roof	EPS 130 mm for severe cold AB area (Hailar, Harbin) EPS 100 mm for severe cold C area (Changchun, Shenyang) EPS 80 mm for cold area (Dalian, Beijing)	
External wall	EPS 100 mm for severe cold AB area (Hailar, Harbin) EPS 80 mm for severe cold C area (Changchun, Shenyang) EPS 70 mm for cold area (Dalian, Beijing)	
Ground	EPS 50 mm for severe cold ABC area (Hailar, Harbin, Changchun, Shenyang) EPS 40 mm for cold area (Beijing, Dalian)	

Table 6. Envelope U-values.

Case Study	U-Values for Different Components (W/m^{2}K)			
	Walls	Windows	Roof	Ground
Severe cold AB				
Concrete block	0.33	2.17		0.48
CLT	0.26	2.17	0.21	0.48
RC			0.28	
Severe cold C				
Concrete block	0.40	2.22		0.48
CLT	0.30	2.22	0.25	0.48
RC			0.35	
Cold area				
Concrete block	0.44	2.34		0.57
CLT	0.32	2.34	0.29	0.57
RC			0.40	

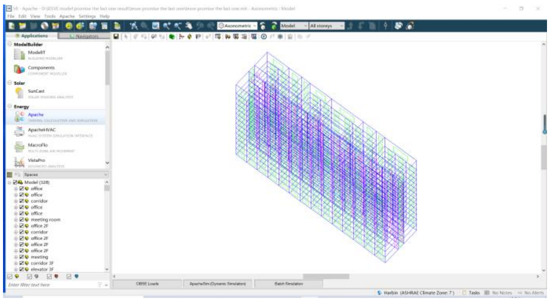
Table 7. Physical property parameters of the material.

Material	Conductivity (W/(m·K))	Density (kg/m^3)	Specific Heat Capacity (J/kg·K)
Concrete block	0.53	800	1000
CLT	0.165	700	2100
RC	1.74	2500	900

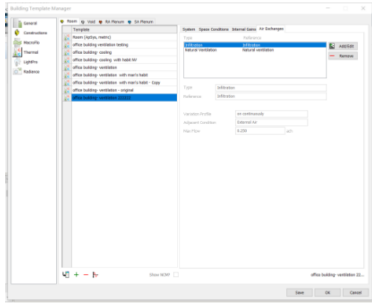
Data source: [56,57].

2.6. Simulation Parameters

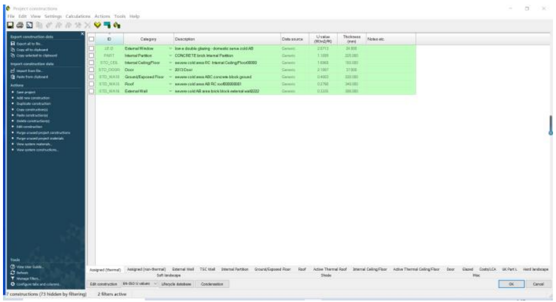
This study simulated the operation of an office building with natural ventilation in the summer, focusing on the indoor air temperature and the inner wall temperature of the envelope. In the IESVE software platform, the concrete and timber were established as separate simulation models (Figure 6). The weather file (EPW) for the six cities is used for the simulations. In accordance with the CIBSE overheating standard, the period from 1 May to 30 September was defined as the simulation period. Below are the details of the simulation parameters.



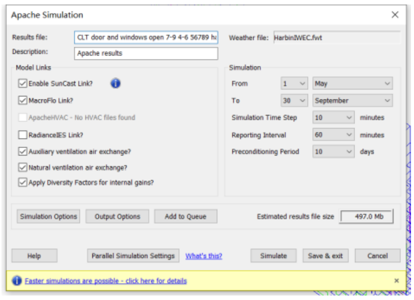
(**a**) The model of office building



(**b**) Building template manager



(**c**) Project construction



(**d**) Apache simulation

Figure 6. IESVE software operation interface.

2.6.1. Simulation Rooms

The building selected for this study is a typical office building in these regions. It is a south-facing office building with 328 rooms, mainly offices with a small number of meeting rooms, and some circulation and equipment spaces. There are 300 offices, 28 of the latter. This paper examined overheating in a typical office unit. The doors to all rooms are kept closed, and each room is a thermal zone (Figure 7). The simulation examines all rooms. In order to evaluate the influence of solar radiation on overheating, the south–north-oriented middle unit room S6 and N6 on the middle floor of 7F are selected as the main research spaces. The room location is shown in Figure 5a and the basic settings are shown in Table 8.

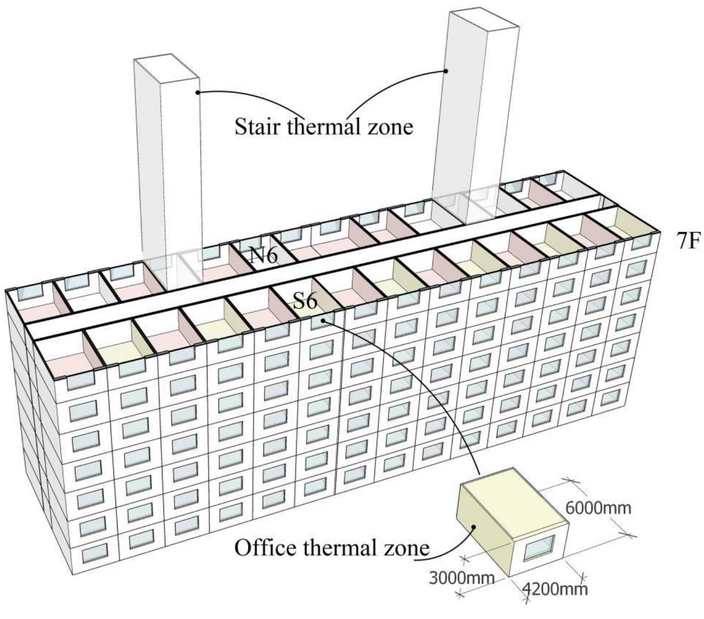


Figure 7. Schematic diagram of building thermal zone.

Table 8. The model parameters.

Input Parameters	Value (for the Building)
Heating	No heating required (free-running during summer)
Heating setpoint/setback temperatures	No setpoint/setback
Ventilation	Natural ventilation—no heating/cooling
Cooling setpoint/setback temperatures	No setpoint/setback temperatures

2.6.2. Ventilation

The office building is considered to be in "free running" during the period from May to September according to the code for the design of public buildings. The basic ventilation parameters are presented in Table 9. This includes the area of the sash window that can be opened and the opening angle. The ventilation time is set according to the behaviour of general office workers. For example, July and August are the hottest months in most parts of China, so windows are defined as open over the entire workday (7:00 a.m.–18:00 p.m.). In May, June and September, the weather is cooler, so the window opening time is shortened to two hours in the morning and afternoon, respectively. The natural ventilation and infiltration air change rates for the office and meeting rooms are set to be 30 $m^3/h/person$ and 0.25 ach.

Table 9. Ventilation parameters for the model.

Related Parameter	Input Parameter	Values	Period
Windows	Openable area	39% open	May, June, September (7:00–9:00,16:00–18:00) July, August (7:00–18:00)
Door	Openable area	100%	Off continuously
Air Exchanges	Infiltration	0.25 ac/h	May–September (00:00–24:00)
	Natural ventilation	8.3 l/s/per	May–September (7:00–18:00)

2.6.3. Appliances and Lighting

The high density of lighting and equipment in office buildings, which results in high internal thermal gains, is a key factor in assessing the risk of overheating in offices [15]. In this simulation, lighting and equipment power were set according to the relevant codes [58]. The number of computers is matched to the number of occupants. Since the office building is free-running, the cooling and heating set-points are not considered in the simulation. Other devices, such as hot water, elevators and other small devices, are not considered as they have less impact on the internal thermal gains in the rooms. Detailed settings are shown in Table 10.

Table 10. Internal gains for the model.

Related Parameter	Input Parameter	Values	Opening Time
Internal Gains	Lighting	9 W/m^2	May–September weekdays (7:00–18:00)
	People	10 $m^2/person$	May–September weekdays (7:00–18:00)
	Computers	30 W/m^2	May–September weekdays (7:00–18:00)

3. Results and Analysis

This study simulated and compared two different envelope structures, including concrete blocks and CLT. Two typical rooms were selected, and the operative temperature inside the room and the internal wall temperature for the outer envelope were modelled. The typical rooms are the south and north rooms S6 and N6, as shown in Figure 4. The experimental results are used to explain the overheating situation in office buildings in the severe cold and cold regions during summer and the relationship between the degree of overheating and the construction materials for the building envelope. The results show that office buildings in the severe cold and cold regions all experience overheating, and the severity of overheating for buildings in the same city is related to the construction materials. At the same time, the current architectural design should update the design strategy to cope with the changing climatic environment.

3.1. The Degree of Overheating

IESVE was used to simulate the overheating situation for office buildings with three different envelope structures in six cities. Table 11 presents the evaluation of room overheating according to the CIBSE TMA standard, which identifies the number of hours during working hours (7:00 a.m.–18:00 p.m.) where the room operative temperature exceeds 25 °C for no more than 5% (conventional not exceeding 125 h), or the number of hours for which the room internal operating temperature exceeds 28 °C for no more than 1% (conventional not exceeding 25 h). The CIBSE standard recommends office building occupancy hours of 2500 h per year. Table 12 evaluates the overheating of the building by using the TM52 Adaptive Comfort analysis tool for the Virtual Environment in IESVE. The tool is based on the criteria outlined in CIBSE Technical Memorandum (TM) 52-2013.

Table 11. Assessment of overheating in concrete brick and CLT buildings (7th floor south S6 room) based on CIBSE TM A.

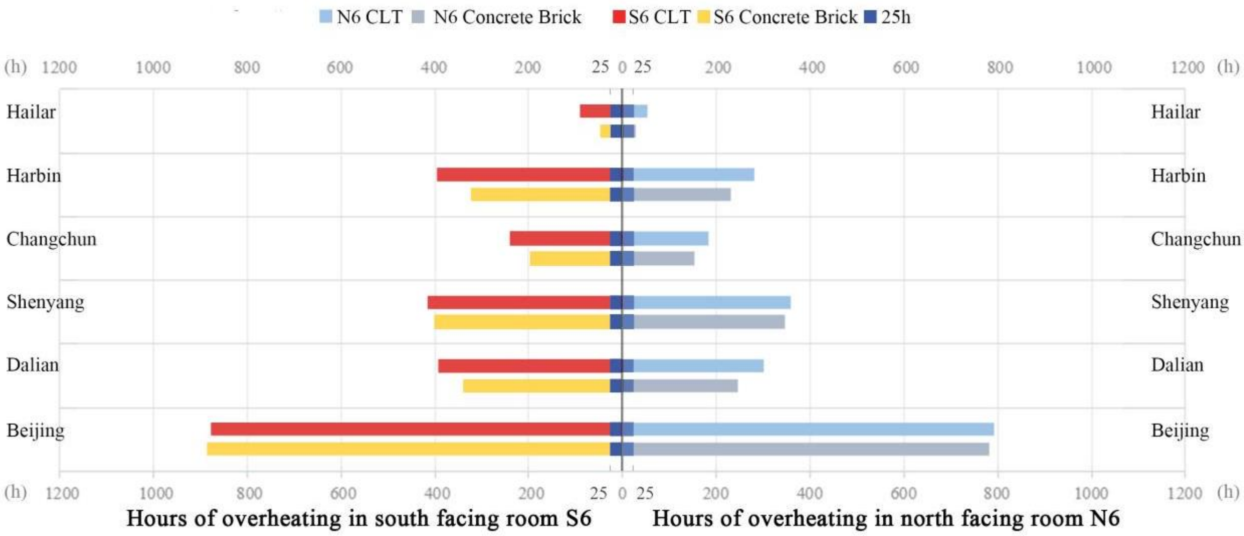
Buildings	Cities	Orientation	Operative Temperature (>25 °C) Office (Hours)	% Time Operative T > 25 °C	Operative Temperature (>28 °C) Office (Hours)	% Time Operative T > 28 °C
Concrete Block Office Buildings	Hailar	South	231	9.24%	46	1.84%
		North	159	6.36%	27	1.08%
	Harbin	South	751	30.04%	323	12.92%
		North	682	27.28%	231	9.24%
	Changchun	South	572	22.88%	198	7.92%
		North	496	19.84%	152	6.08%
	Shenyang	South	807	32.28%	401	16.04%
		North	702	28.08%	347	13.88%
	Dalian	South	755	30.20%	341	13.64%
		North	728	29.12%	245	9.80%
	Beijing	South	1084	43.36%	887	35.48%
		North	1057	42.28%	781	31.24%
CLT Office Building	Hailar	South	271	10.84%	89	3.56%
		North	200	8.00%	53	2.12%
	Harbin	South	779	31.16%	395	15.80%
		North	693	27.72%	282	11.28%
	Changchun	South	619	24.76%	239	9.56%
		North	526	21.04%	183	7.32%
	Shenyang	South	824	32.96%	416	16.64%
		North	733	29.32%	358	14.32%
	Dalian	South	791	31.64%	392	15.68%
		North	749	29.96%	302	12.08%
	Beijing	South	1071	42.84%	877	35.08%
		North	1052	42.08%	792	31.68%

Table 12. Assessment of overheating in concrete block and CLT buildings (7th floor S6) based on CIBSE TM 52.

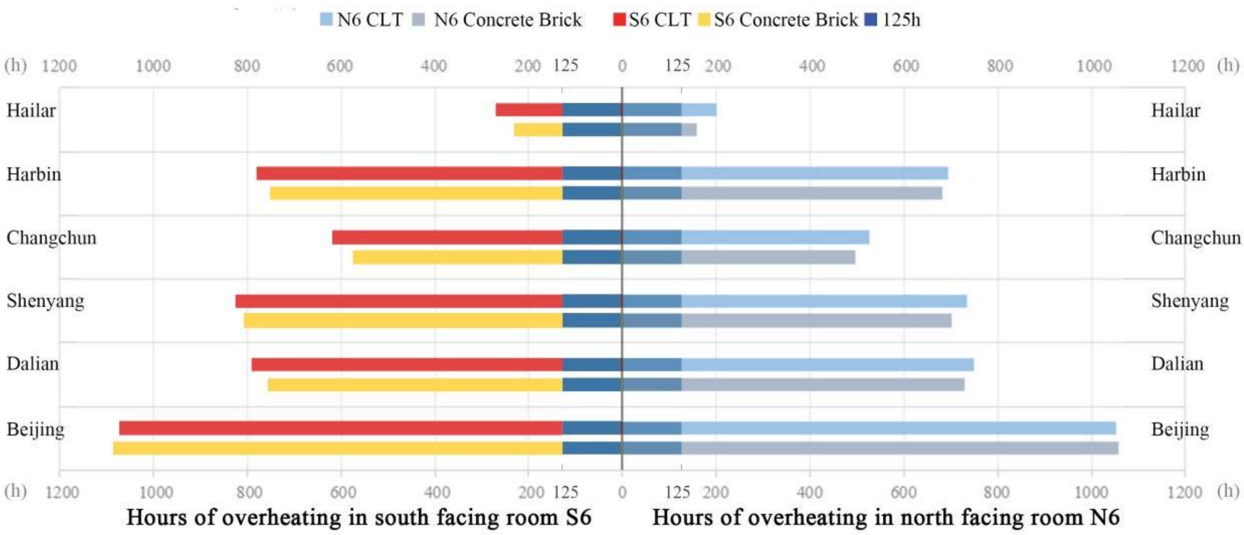
Building Material	Cities	Orientation	Criteria 1 (% Hrs Top-Tmax > = 1 K)	Criteria 2 (Max. Daily Deg. Hrs)	Criteria 3 (Max. DeltaT)	Criteria Failing	Overheating
Concrete Block Office Buildings	Hailar	South	2	9	4	2	No
		North	0.7	4	2		No
	Harbin	South	15	29	4	1 & 2	Yes
		North	8.3	21	3	1 & 2	Yes
	Changchun	South	4.8	26	4	1 & 2	Yes
		North	2.1	18	3	2	No
	Shenyang	South	14.2	20	3	1 & 2	Yes
		North	7	12	2	1 & 2	Yes
	Dalian	South	9.4	11	2	1 & 2	Yes
		North	0.3	3	1		No
	Beijing	South	51.3	44	5	1 & 2 & 3	Yes
		North	34.9	38	5	1 & 2 & 3	Yes
CLT Office Buildings	Hailar	South	6.8	34	6	1 & 2 & 3	Yes
		North	2.5	19	5	2 & 3	Yes
	Harbin	South	23.3	44	6	1 & 2 & 3	Yes
		North	14.2	34	5	1 & 2 & 3	Yes
	Changchun	South	13	53	7	1 & 2 & 3	Yes
		North	6.6	41	6	1 & 2 & 3	Yes
	Shenyang	South	20	35	6	1 & 2 & 3	Yes
		North	13.2	27	4	1 & 2	Yes
	Dalian	South	14.5	19	4	1 & 2	Yes
		North	3.8	11	3	1 & 2	Yes
	Beijing	South	52.7	63	8	1 & 2 & 3	Yes
		North	40.5	56	7	1 & 2 & 3	Yes

3.1.1. CIBSE TMA

The results show that office buildings in six representative cities have different degrees of overheating (Figures 8 and 9, Tables 11 and 12). At higher latitudes, such as Hailar, overheating is not so obvious. The overheating degree in the six cities gradually increases from severe cold A to cold 2B. CLT buildings are generally more likely to overheat than concrete block buildings. The number of overheating hours in CLT buildings is up to 2.88% (72 h) more than that in concrete buildings.



(**a**) Number of hours > 25 °C



(**b**) Number of hours > 28 °C

Figure 8. Number of hours > 25 °C or > 28 °C in six cities according to CIBSE TM52.

The results also show a significant difference in the number of overheating hours between the south-facing room and the north facing room in the severe cold and cold regions. Taking 25 °C as the standard, the percentage of overheating hours during working time on the south side can be 19–105 h more than that on the north side. Taking 28 °C as the standard, the percentage of overheating hours on the south side of the room can be 19–113 h more than that on the north side. These differences will vary with different climatic conditions and different envelope materials.

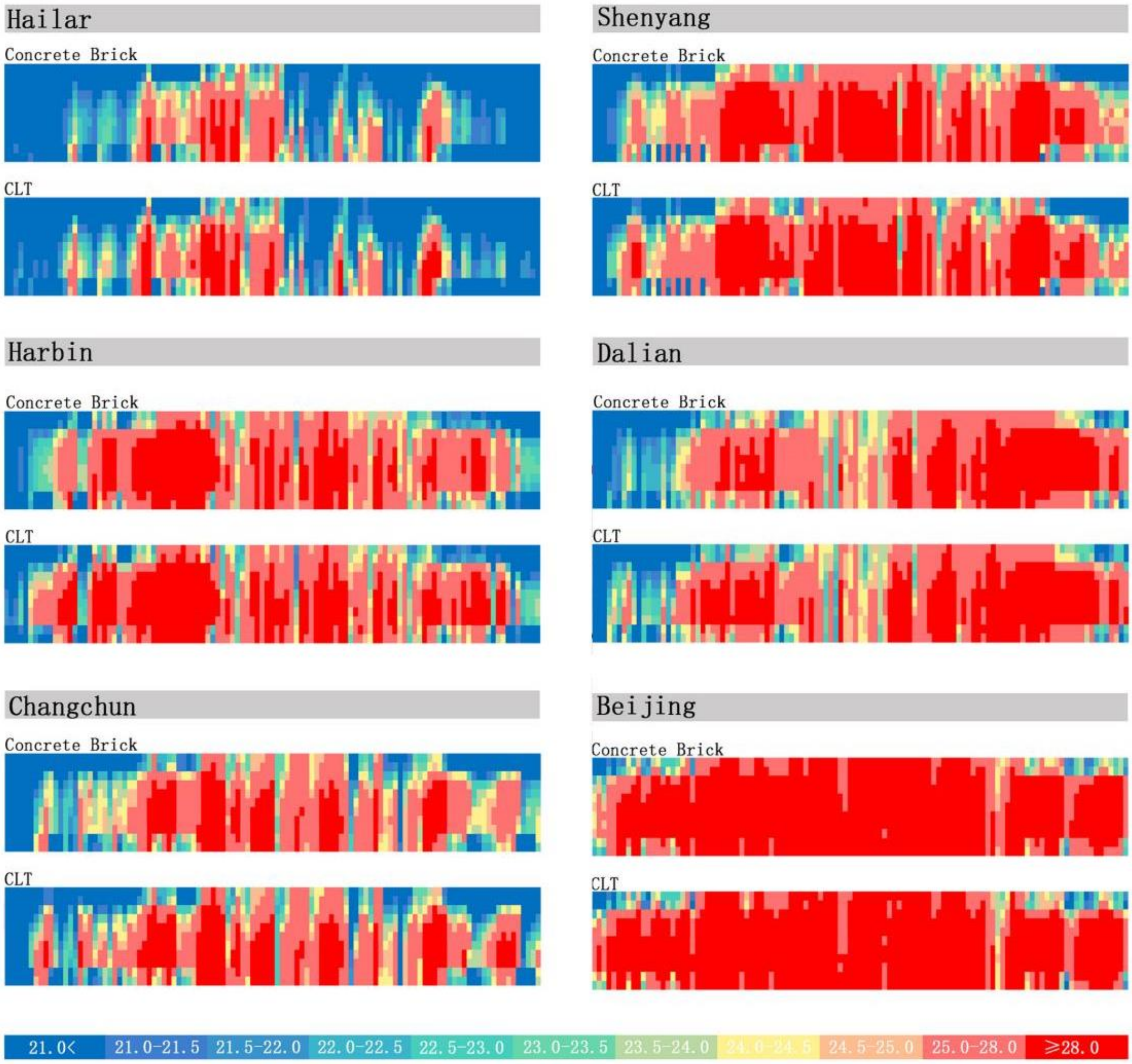


Figure 9. Operative temperature (°C) in the south room at 7F in six cities for concrete and CLT construction.

In Figure 9, the light red area indicates that the operating temperature of the S6 office at 7F during this period exceeds 25 °C, and the dark red area indicates that the operating temperature exceeds 28 °C. According to the CIBSE TMA standard, the red area refers to the overheating period. The figure presents the overheating for the three different envelopes in the six cities (the condition is for working hours from May to September, not including weekends). As shown in Figure 6, as the geographical location of the city moves from north to south, the duration of overheating in the room gradually increases from 38 days to 108 days. Beijing has the most serious overheating issue with the longest duration (about 108 days), with almost no interruption during the whole simulation period. In the other five cities, the overheating period is interrupted to varying degrees during the simulation period. In terms of the different materials, the overheating duration in CLT buildings is longer than that in concrete buildings.

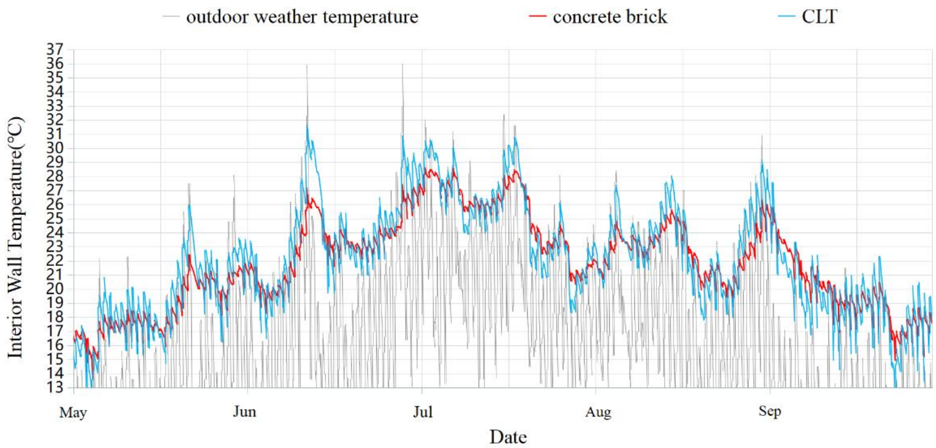
3.1.2. CIBSE TM52

CIBSE TMA is a static evaluation standard for overheating. It only considers the influence of temperature but does not consider the duration of overheating and other parameters that can affect thermal comfort. CIBSE TM52 is a dynamic evaluation standard, which more accurately evaluates the degree of overheating. In this study, the TM52 Adaptive Comfort Analysis Tool was used for the Virtual Environment in IESVE. Specific data are shown in Table 12. Human clothing, activity state and indoor wind speed are defined. The same rooms 7F, S6 and N6 rooms are selected as the test rooms. The results showed that, except for Hailar, the other cities have varying degrees of overheating risk. According to the TM52 standards, the test room in Hailar was not overheated. However, according to the CIBSE TMA standard, the test room is deemed to be overheated. This suggests that the Hailar overheating situation is not serious. The results also show that concrete buildings are more likely to overheat than CLT buildings. In addition, the degree of overheating in the north and south test rooms is also significantly different. There is significantly more overheating in the south facing room than the north facing room.

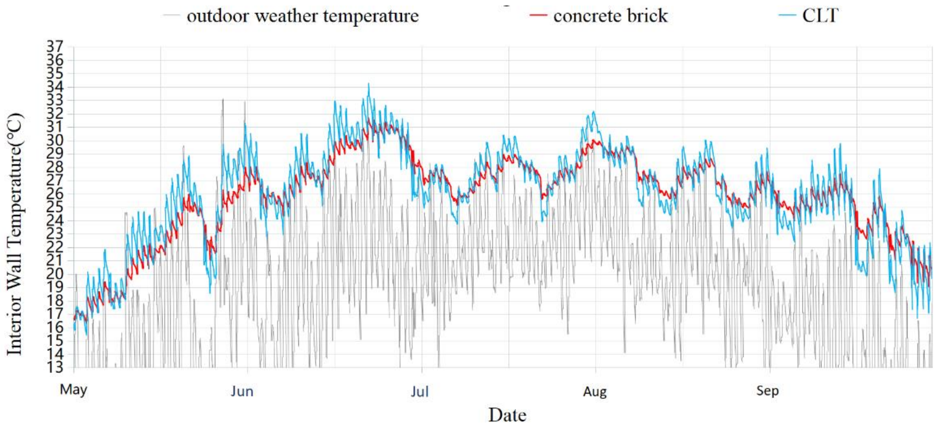
3.2. The Wall Inner Surface Temperature

The internal overheating of the room is evaluated according to the CIBSE standard, and the results showed that the concrete block building has a lower degree of overheating than the CLT. The average inner wall temperature of the CLT building is 0.4 °C higher than in the concrete building.

This section calculates the inner wall temperature for the two different envelope structures. South-facing room S6 is selected as the research object. The data for May to September in the six typical cities are summarised in Figure 10. It can be seen that the concrete block walls have a reduced temperature fluctuation with outdoor temperature compared to that of CLT buildings. Based on the internal wall temperature line chart and previous studies, it can be confirmed that the thermal performance of concrete is superior to CLT.

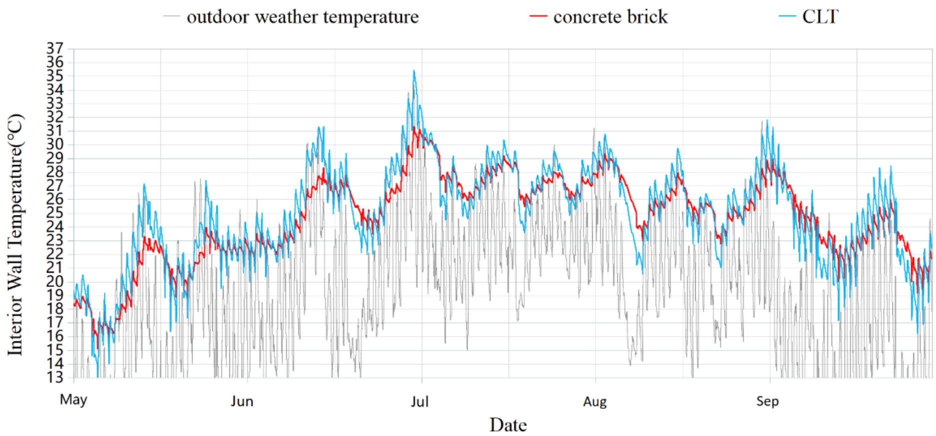


(**a**) Hailar

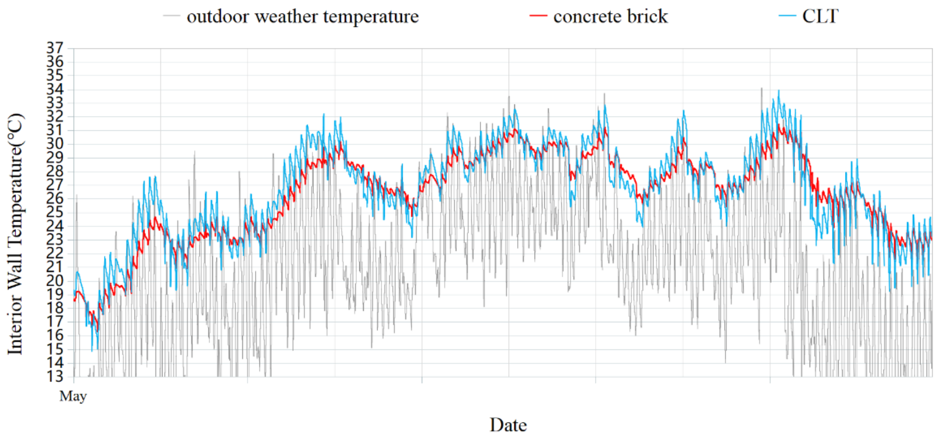


(**b**) Harbin

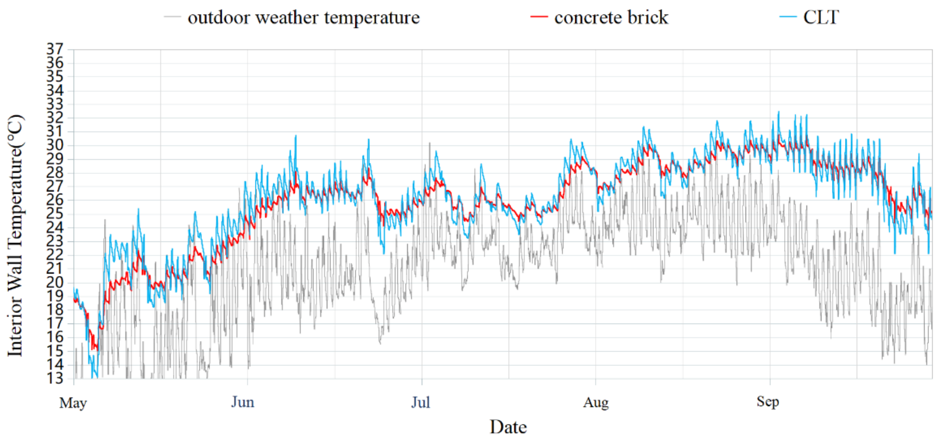
Figure 10. *Cont.*



(**c**) Changchun

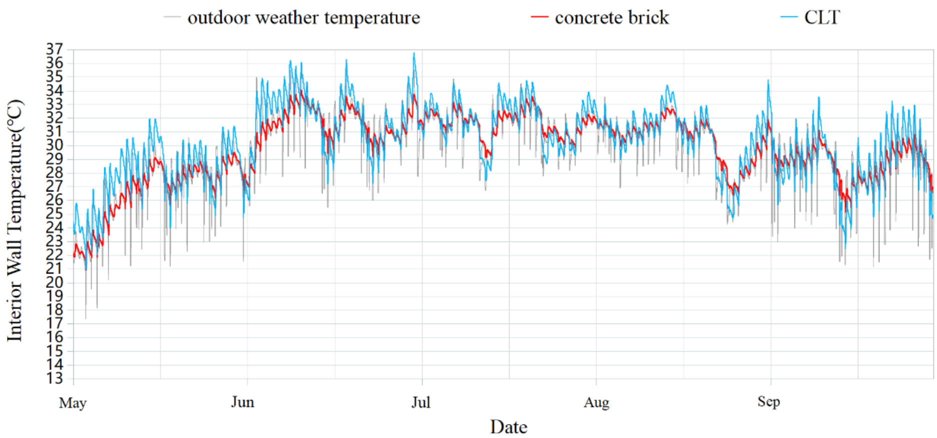


(**d**) Shenyang



(**e**) Dalian

Figure 10. *Cont*.



(**f**) Beijing

Figure 10. Comparison of concrete brick and CLT interior wall temperature in six cities from 1 May to 30 September.

4. Discussion

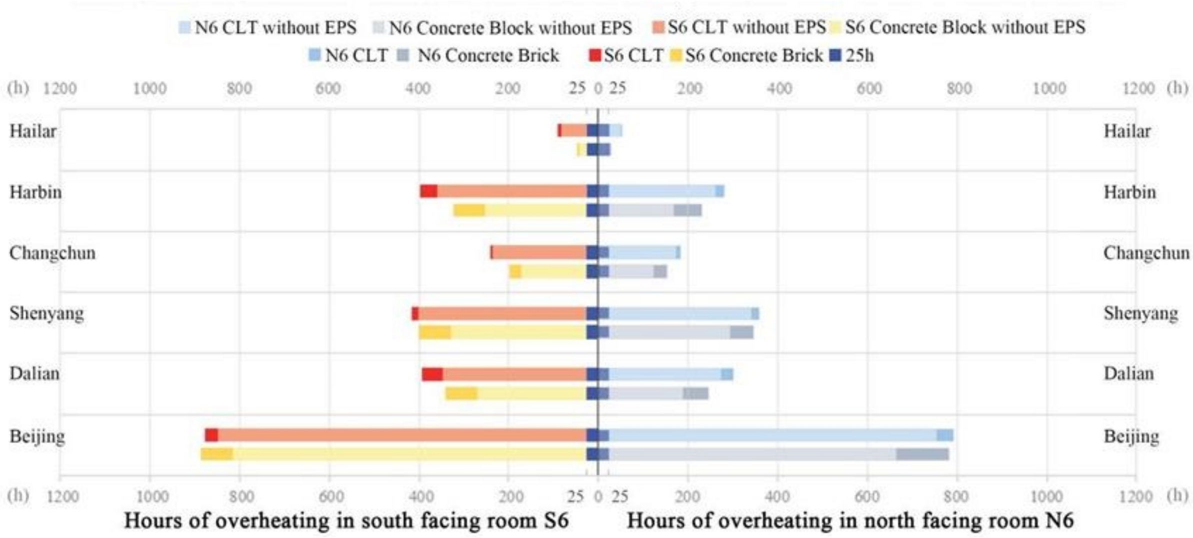
(1) Suggestions for the revision of building design code

External shading should be considered for office buildings in severe cold regions and cold region A. Currently, the design standard for energy efficiency in public buildings does not include relevant regulations on whether external shading measures should be implemented in severe cold regions. The code for the thermal design of civil buildings clearly indicates that buildings in severe cold regions and cold region A need not consider external shading of buildings. However, global warming and the continuous pursuit of energy-efficiency with low U-values in the severe cold and cold regions have introduced the phenomenon of summer overheating in these regions. Currently building regulations in China do not account for the health and environment risks from overheating, nor do they suggest measures which need to be taken into account to alleviate these. In order to alleviate risks in the future, steps need to be taken now rather than later. China should develop evaluation criteria for overheating similar to CIBSE TMA, CIBSE TM52 and include these in the building codes. Research has shown that unless the way buildings are designed, built and operated changes significantly in the next few decades, construction owners will face a significant increase in operating costs, which will put enormous pressure on energy systems [9].

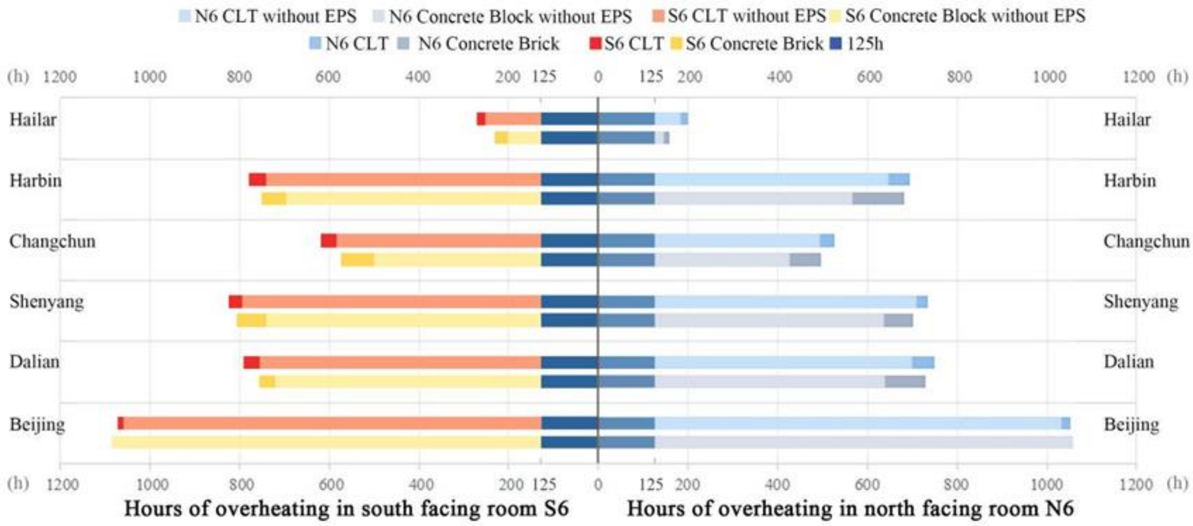
(2) The effect of heat insulation materials on overheating

In order to save energy during winter in China's severe cold and cold regions, the building envelope incorporates a thick insulation layer. This insulation is thought to be one of the causes of overheating, but no detailed studies have been performed for China's frigid regions. This study simulates the overheating situation for CLT and concrete buildings with and without the insulation layer during summer, respectively, and compares the two situations. In the contrast experiment, the summer overheating time of the same building with or without an insulation layer is simulated in the severe cold and cold regions of China. The purpose is to demonstrate that the higher insulation layer increases the overheating risk during summer and may have a negative impact on indoor heat dissipation during summer.

This comparison (Figure 11) shows that the insulation layer can indeed aggravate building overheating, and the influence of this insulation layer with the same thickness on the concrete block is greater than on CLT. When the insulation layer is removed, the number of overheating hours inside the concrete block room reduces by 27–71 h according to the overheating standard of 25 °C, and 3–72 h according to the overheating standard of 28 °C. For CLT buildings, after removing the insulation layer, the corresponding reduction is 11–37 h for 25 °C, and 6–38 h for 28 °C. The inner wall temperature for the concrete wall with an insulation layer is 1.1–1.5 °C higher than that for the wall without insulation. For CLT walls, the inner wall temperature with insulation is 0.4–0.7 °C higher than without insulation. This varies with the location of the building and the thickness of the insulation. Taking Harbin as an example (Figure 12), the wall with an insulation layer has better thermal stability than the wall without insulation, but it is also more likely to overheat. The average interior surface temperature of the CLT building with insulation is 0.5 °C higher than that without insulation. The average interior surface temperature of concrete buildings, in contrast, is 1.5 °C higher than that without insulation.

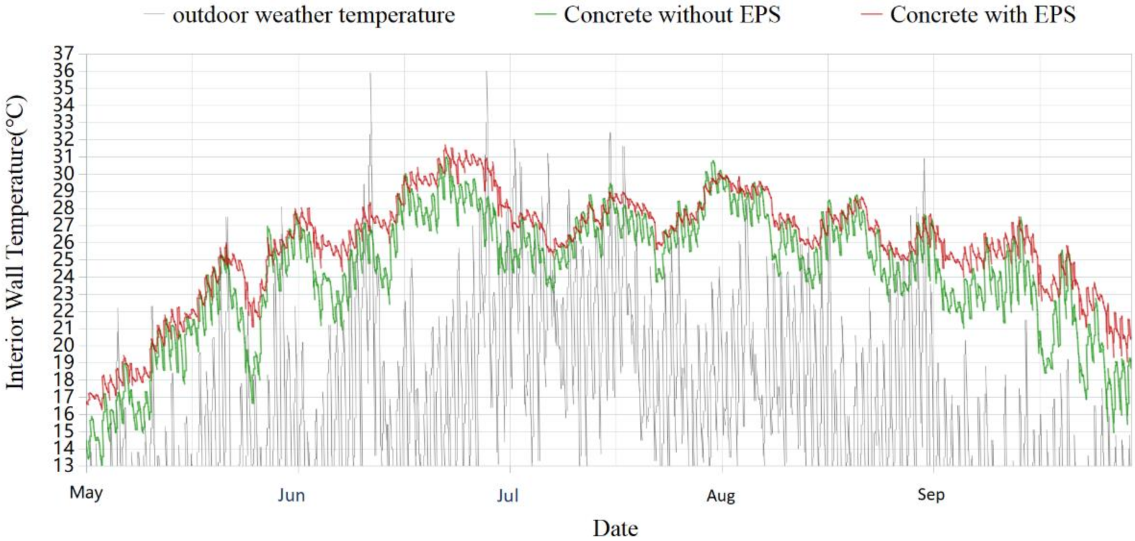


(**a**) The number of hours of indoor room air temperature above 28 °C in 7F

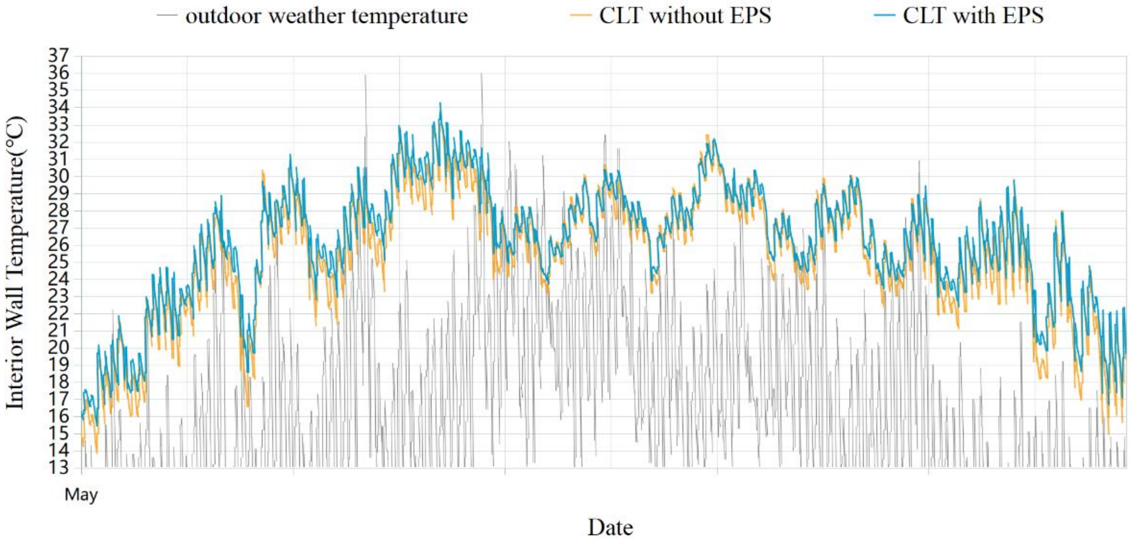


(**b**) The number of hours of indoor room air Temperature above 25 °C in 7F

Figure 11. Comparison of hours of overheating in concrete and CLT buildings with and without insulation in six cities.



(**a**) Concrete



(**b**) CLT

Figure 12. Comparison of interior wall surface temperatures for different construction materials with and without insulation during May to September in Harbin.

(3) Potential methods to alleviate overheating

Office buildings in severe cold and cold regions have different degrees of overheating depending on the different climate and envelope materials. Given the global energy crisis and the low carbon target, passive measures should be given priority to alleviate the risk of building overheating. The office building is not used at night, so night ventilation is a suitable way to reduce overheating. Solgi et al. (2018) showed that night ventilation can effectively improve thermal comfort in buildings in most climate types [59]. Studies have also shown that night ventilation has greater energy saving potential for public buildings in cold climate regions during summer [60,61]. Shading measures can also be used to slow southern overheating. This research shows a clear difference between the degree of overheating in the north and south orientation. This is largely due to direct solar radiation. For some lightweight buildings, summer overheating can be alleviated by appropriately increasing the thermal mass inside the building. The use of phase change materials (PCMs) may also be considered to mitigate the risk of overheating.

5. Conclusions

This paper focused on the overheating of office buildings in the severe cold and cold regions of China. The overheating conditions for two kinds of envelope materials were compared, namely those of concrete and CLT. The influence of the insulation layer on building overheating was also discussed. The main research method was software simulation. The principal conclusions are as follows:

(1) All the studied office buildings in the severe cold and cold regions in China suffered different degrees of overheating problems during summer, particularly those with natural ventilation. In China, office buildings built with concrete or CLT are at risk of overheating in the severe cold and cold regions. The severity of overheating depends on the location of the building, the climate, the building material and the orientation of the rooms. According to CIBSE TMA, office room temperatures above 25 °C during summer (May–September) occur in Hailar, Harbin, Changchun, Shenyang, Dalian and Beijing for 6.36–10.84%, 27.28–31.16%, 19.84–24.76%, 28.08–33.08%, 29.12–31.64% and 42.08–43.56% of the total occupied time, respectively. The percentage fluctuates depending on the building materials used in the office building and the orientation of the test rooms. According to CIBSE TM52, office buildings in the cities in this study also have different degrees of overheating.

(2) Based on the research results, the local building regulations for severe cold and cold regions need be promoted. In the Chinese office building codes, there are no relevant regulations for the shading of public buildings in severe cold areas. This code should be modified to adapt to the changing environment.

(3) The potential overheating is closed related to the building materials. In the severe cold and cold regions of China, overheating in CLT buildings is more pronounced than in concrete buildings during summer. The number of overheating hours of CLT buildings can be as much as 2.88% (72 h) more than in concrete buildings. The average inner wall temperature in CLT buildings is up to 0.4 °C more than in concrete buildings.

(4) A thick insulation layer aggravates the degree of building overheating, and the impact is greater on the concrete building. Concrete buildings with an insulation layer have 27–71 h more overheating than buildings without insulation, while CLT buildings only show an increase of 11–37 h with insulation.

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