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A new method for calculating the thermal effects of irregular internal mass in buildings under demand response

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ABSTRACT

Accurately modeling thermal storage and discharge play a pivotal role in predicting the peak savings of demand response buildings. Considerable studies have been conducted on the transient thermal behavior of building envelopes, much of which has focused on the thermal mass effects of building envelopes and floors. However, it is unclear how to precisely describe the cooling storage effects of irregular internal mass such as furniture. EnergyPlus and other simulation tools have internal mass models, but these models require ambiguous inputs such as internal mass surface area, thickness, volume and thermal properties. These inputs are impossible to obtain due to the irregular shapes and random spatial distributions of internal mass. In this paper, the novel "Effective Area" method is proposed that improves the theory of the conventional "Equivalent Slab" method. The new method establishes a relationship between the actual furniture and the equivalent furniture through a converted coefficient in the dynamic heat transfer equations. Experiments are conducted to test and verify the accuracy of the new method and to calculate common parameters, such as the converted coefficient and the distribution density of the irregular internal mass in some typical office setups.

1. Introduction

Buildings consume approximately 30% of global primary energy and generate 30% of energy-related CO_2 emissions; approximately 65% of building energy consumption is due to heating, ventilation and air-conditioning systems [1,2]. In addition to the large amount of energy use, the peak electricity demand of buildings increases simultaneously, which jeopardizes the reliability of the grid. Recently, demand response (DR) has become a promising concept in the electricity market [3]. DR refers to tariffs or programs designed to motivate end-use customers by responding to changes in the price or availability of electricity over time by changing their normal patterns of electricity use. DR normally uses incentive payment programs to reduce the electricity usage when grid reliability is jeopardized [4].

DR has been recognized as an important passive method to reduce the peak electricity demand of buildings by utilizing building thermal mass to shift the HVAC load, which has been demonstrated in many simulations, experiments and field studies [5–7]. Therefore, the accurate modeling of thermal mass effects is a pivotal issue for the load shifting studies of HVAC systems. The thermal mass of a building can shift the HVAC load because this mass absorbs and stores the cooler energy when the indoor temperature is low and releases this cool when the indoor temperature is high, reducing the fluctuation and delaying the peak time of the indoor temperature oscillations [8].

Building thermal mass involves all objects in buildings, including building envelopes, furniture and even indoor air. According to their location, thermal mass can be classified into external thermal mass and internal thermal mass [9]. The external thermal mass refers to the external envelope of the building, such as exterior walls and roofs. Substantial studies have been conducted to study the transient thermal behavior of walls, such as the frequency domain and time domain [10,11], lumped parameter method [12,13], numerical methods [14] and employing dynamic system models derived from actual building performance data [15]. These methods can accurately describe the dynamic thermal behavior of external thermal mass to some extent.

However, the external thermal mass is exposed to both the outdoor and indoor environments because it connects the outdoor and indoor environments [16], which means the exposure of external envelope of building to internal environment change is limited. Therefore, Balcomb [17] considered that the thermal storage effect

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Nomenclature

A_e	Heat transfer area between envelope and indoor air, m^2
A_f	Heat transfer area between furniture and indoor air, m^2
$A_{f,equ}$	Equivalent area of furniture, which is corresponding to $C_{f,equ}$ m^2
$A_{f,eff}$	Effective area of furniture, which is corresponding to $C_{f,cal}$ m^2
$A_{f,cal}$	Calculation area of furniture, m^2
$A_{T_{out}}$	Outdoor temperature amplitude
$A_{T_{in}}$	Indoor temperature amplitude
a	Thermal diffusivity, m^2/s
Bi	Biot number
$C_{f,cal}$	Calculation capacity of furniture, W/K
$C_{f,equ}$	Equivalent capacity of furniture, which is corresponding to $A_{f,equ}$ W/K
c	Specific heat, J/(kg K)
h_e	Convective heat transfer coefficient between envelope and air, $W/m^2 \cdot K$
$h_{e,rad,in}$	Radiation heat transfer coefficient between envelope indoor wall surfaces and other surfaces, $W/m^2 \cdot K$
h_f	Convective heat transfer coefficient between furniture and indoor air, $W/m^2 \cdot K$
$h_{f,rad}$	Radiation heat transfer coefficient between furniture and other surfaces, $W/m^2 \cdot K$
h_p	Onvective heat transfer coefficient between internal partition and indoor air, $W/m^2 \cdot K$
L_f	Size dimension of furniture, m
m_f	Furniture quality, kg
Q_{ac}	Controllable heat source, W
Q_e	Heat conduction of the envelope, W
Q_f	Heat transfer of the furniture, W
Q_p	Heat transfer of the internal partition, W
$Q_{f,rad,in}$	Furniture radiation heat gain from indoor objects. W
$Q_{f,solar}$	Furniture radiation heat gain from solar source. W
Q_{in}	Uncontrollable heat source, W
Q_{inf}	Heat gain of infiltration and ventilation, W
ΔQ_f	Increased heat of furniture, W
$q_{in,rad}$	Radiation heat of heat source, W/m^2
q_{solar}	Average heat flux of the solar source through the window, W/m^2
T_{ave}	Average temperature of indoor partition surfaces, °C or K
T_e	Envelope temperature, °C or K
T_f	Furniture surface temperature, °C or K
T_p	Internal partition temperature, °C or K
$T_{f,ave}$	Furniture average temperature, °C or K
T_{in}	Indoor air temperature, °C or K
T_{out}	Comprehensive temperature (considering radiation) of outdoors or outdoor dry bulb temperature(without considering radiation), °C or K
t	Time, s
V_a	Air volume, m^3
α	Ratio of absorbed heat to the whole solar radiation
β	Ratio of $C_{f,equ}$ to $C_{f,cal}$
γ	Ratio of $A_{f,eff}$ to $A_{f,cal}$
δ	Relative error
ζ	Ratio of $A_{f,equ}$ to $A_{f,cal}$, unknown and depend on experience
η	Ratio of absorbed heat to the whole heat source radiation
λ	Heat conductivity coefficient, $W/m \cdot K$
ν_T	Indoor decrement coefficient
ξ_T	Time lag, s
ρ	Density, kg/m3
σ	Thickness of object, m
ω	Frequency of the temperature fluctuation, $2\pi/24^{-1}$

Subscripts

a	Air
e	Envelop
f	Furniture
p	Internal partition
in	Indoor
out	Outdoor

of internal thermal mass is better than that of external thermal mass.

The internal thermal mass can be classified into the fixed portion and the unfixed portion. The fixed portion includes building partitions that do not move. The unfixed portion includes furniture that can be moved and added [18]. The analysis of the transient thermal behavior for a building partition is similar to that of the building envelope. The main difference lies in the boundary conditions: both sides of the building partition are exposed to the indoor environment. However, the shape of the unfixed portion is always irregular, and the distribution is random; therefore, an accurate description of the irregular internal thermal mass (hereinafter referred to as "furniture") is difficult. However, the calculation of this thermal mass is important in the DR analysis when shifting the HVAC load using building thermal mass effects. Some simplified and equivalent methods are proposed to analyze the thermal behavior of furniture.

The simplest method ignores the role of internal mass, assuming that the temperature of the internal thermal mass is isothermal with the indoor air in real time. In some DR studies of HVAC systems [19–21], the dynamic heat transfer models use only a total heat capacity to denote both indoor air and internal mass and use one node to indicate the temperature of both. In the building transient system simulation program TRNSYS [22], TYPE 56, which simulates the building transient thermal behavior, also uses one temperature node to describe the indoor air and surrounding internal mass. Zhou J et al. presented a simplified model considering both internal and external thermal mass that assumed that the temperature over the internal thermal mass surface was the same as the indoor air temperature [16]. However, they later noted that the model is not accurate because the actual temperature of the internal thermal mass is not equal to the indoor air temperature [23]. Antonopoulos found that typical indoor mass increases the time constant and thermal delay by up to 40%, which is split to 25% for interior partitions and 15% for furnishings [18]. Therefore, it is not accurate to use one temperature node for both the indoor air and internal mass. Especially for DR research, the cooling capacity of the HVAC system will be decreased during the DR event to realize peak demand reduction. The reduced cooling load will lead to increased indoor air and building thermal mass temperature. However, the indoor air and internal mass temperatures will increase at different rates because of their different thermal capacities. Therefore, the temperature difference between the indoor air and the internal mass will influence the accuracy of DR control strategies.

Apart from the abovementioned methods, a better and more common approach is to convert the actual furniture into a regular shape without changing its thermal behavior [16]. Antonopoulos [24] employed a slab to represent furniture and used the one-dimensional transient heat conduction equation to process the heat transfer of the slab, which is called the “Equivalent Slab” method. The building energy simulation programs EnergyPlus [25] and DeST [26] also adopt the “Equivalent Slab” method to describe furniture. Furthermore, the “Virtual Sphere” [23] method considers non-isothermal internal mass and non-uniform materials and lumps different shapes and types into one virtual sphere based on the theory that the temperature variation trends are the same when the Fourier numbers are the same.

Because DR studies focus on controlling indoor air temperature within the comfort zone, the ideal method is supposed to consider the influence of furniture on the indoor air temperature. Therefore, compared to the “Equivalent Slab Method”, the “Virtual Sphere” method is not a suitable simplified method because it focuses on describing the temperature difference inside the object. However, it is not necessary to describe the detailed non-uniform temperature distribution of furniture. So far, no studies have provided a process for using the “Equivalent Slab” method, such as how to convert the furniture of a given building into an equivalent slab or the conversion function between actual furniture and equivalent furniture. Furthermore, in the Equivalent Slab method, users input the thickness, area and other physical parameters of the slab. No typical inputs based on typical buildings have ever been tested or determined. Therefore, a new method called the “Effective Area” method is proposed in this paper. Inputs include the physical parameters of the actual furniture, such as mass and material properties. Finding these values is relatively easy. The “Effective Area” method can be used to obtain the conversion function and the description of equivalent furniture in building transient thermal models.

This paper is organized as follows: First, Section 2 analyses the thermal energy balance of indoor air. In Section 3, the proposed “Effective Area” method is introduced and compared with the “Equivalent Slab” method to demonstrate the advantages of this new method. Section 4 presents an experimental setup with varying furniture density and obtains the conversion coefficient of the effective area for the different densities. Finally, Section 5 briefly concludes the research on the “Effective Area” method.

2. Theory of the indoor air thermal energy balance

Analyzing the dynamic heat transfer in buildings shows that the transient indoor temperature mainly depends on heat transfer among the envelope, internal partitions and irregular objects (e.g., indoor furniture) as well as the infiltration, ventilation and indoor heat sources. These parameters can be divided into controllable heat sources such as the terminals of the air conditioning system and uncontrollable heat sources such as personnel, lighting and computers. The thermal energy balance of indoor air is shown in Fig. 1, and the instantaneous heat balance of indoor air can be expressed as shown in Eq. (1):

$$\rho_a V_a c_a \frac{\partial T_{in}(t)}{\partial t} = \sum_e Q_e(t) + \sum_f Q_f(t) + \sum Q_{in}(t) + \sum Q_{ac}(t) + \sum Q_{inf}(t) \quad (1)$$

where $\sum_e Q_e(t)$ refers to the heat conduction of the envelope and partitions, $\sum_f Q_f(t)$ is the heat transfer of the furniture, $\sum Q_{in}(t)$ and $\sum Q_{ac}(t)$ are the heat transfers of the uncontrollable and controllable heat sources, respectively, and $\sum Q_{inf}(t)$ denotes the heat gain of infiltration and ventilation.

2.1. Envelope and partition heat transfer analysis

The heat transfer of the envelope is expressed by the following equation, Eq. (2):

$$Q_e = \sum h_{e,in}\left(T_{e,in} - T_{in}\right) A_e \quad (2)$$

Transient one-dimensional heat conduction in the envelope can be expressed as Eq. (3):

$$\frac{\partial T_e}{\partial t} = a_e \frac{\partial^2 T_e}{\partial {x_e}^2} 0 \le x_e \le \sigma_e, t > 0 \quad (3)$$

The boundary conditions at the outdoor and indoor wall surfaces can be expressed as Eq. (4) and Eq. (5):

$$-\lambda_e \left(\frac{\partial T_e}{\partial x_e}\right)_{x_e=0} = h_{e,out}\left(T_{out} - T_{e,out}\right) \quad (4)$$

$$-\lambda_e \left(\frac{\partial T_e}{\partial x_e}\right)_{x_e=\sigma_e,} + \alpha_e q_{solar} + h_{e,rad,in}\left(T_{e,in} - T_{ave}\right) + \eta_e q_{in,rad} = h_{e,in}\left(T_{e,in} - T_{in}\right) \quad (5)$$

Transient one-dimensional heat convection and the corresponding boundary conditions of the interior partitions, floors or ceilings are similar to Eqs. (2)–(5). The differences are that in the boundary conditions, the indoor and outdoor air parameters should be replaced by the corresponding air parameters of the interior partitions, floors or ceilings that the indoor air touches.

2.2. Furniture heat transfer analysis

The heat transfer of the furniture is expressed by Eq. (6):

$$Q_f = \sum h_f\left(T_f - T_{in}\right) A_f \quad (6)$$

Due to the furniture's irregular shape and random distribution as described in the previous section, it is necessary to find a general method to calculate the heat transfer of the furniture, transforming them into regular equivalent objects such as a slab, cylinder or sphere whose heat transfer is easy to calculate.

The present study proposed the “Effective Area” method that transforms the irregular furniture to a slab with a certain thickness. Unlike the “Equivalent Slab” method, this method considers the slab as an isothermal object. The new method uses the lumped parameter method instead of transient one-dimensional heat transfer to analyze the dynamic heat transfer characteristics of the furniture. Through this simplification, the conversion relationship between the actual furniture and a regular equivalent object can be obtained by utilizing the easily available parameters of the original furniture.

The heat transfer process over a certain time is shown in Fig. 2.

Usually, the thermal energy balance equation of furniture can be expressed as shown in Eqs. (7)–(9):

$$\frac{\partial T_f}{\partial t} = a_f \frac{\partial^2 T_f}{\partial {x_f}^2} 0 \le x_f \le \sigma_f/2, t > 0 \quad (7)$$

$$-\lambda_{f,0}\left(\frac{\partial T_f}{\partial x_f}\right)_{x_f=0} = 0 \quad (8)$$

$$\alpha_f q_{solar} A_{f,equ} + h_{f,rad}\left(T_{f,\frac{\sigma_f}{2}} - T_{in}\right) A_{f,equ} + \eta_f q_{in,rad} A_{f,equ} = h_f\left(T_{f,\frac{\sigma_f}{2}} - T_{in}\right) + \lambda_{f,\frac{\sigma_f}{2}}\left(\frac{\partial T_f}{\partial x_f}\right)_{x_f=\frac{\sigma_f}{2}} \quad (9)$$

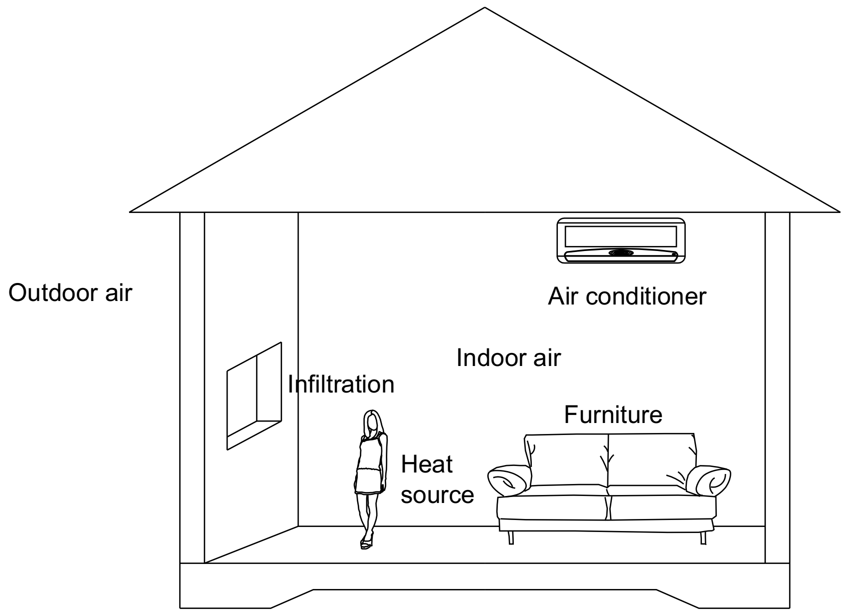


Fig. 1. Thermal energy balance of indoor air.

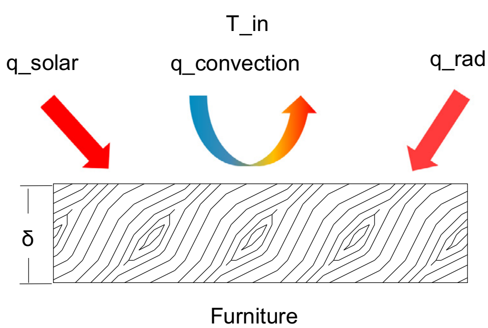


Fig. 2. Heat transfer of furniture.

In the "Effective area" method, first, the heat capacity of all of the furniture is lumped as $C_{f,equ}$, which is a time variable. The thermal energy balance can be expressed as shown in Eqs. (10)–(11)), and Eq. (11) is a lumped form of Eqs. (7)–(9):

$$Q_{f,solar} + Q_{f,rad,in} = Q_f + \Delta Q_f \quad (10)$$

$$\alpha_f q_{solar} A_{f,equ} + h_{f,rad}\left(T_f - T_{ave}\right) A_{f,equ} + \eta_f q_{in,rad} A_{f,equ} = h_f\left(T_f - T_{in}\right) A_{f,equ} + C_{f,equ}\frac{dT_f}{dt} \quad (11)$$

where $A_{f,equ}$ and $C_{f,equ}$ represent the area and the instantaneous heat capacity of the equivalent slab, respectively. According to the equation, the calculation procedure could be simplified if we can obtain the value of $C_{f,equ}$ in the heat transfer process. $C_{f,equ}$ is a function of material density, heat capacity, furniture size and time; the first three are constant for a given set of furniture. Therefore, $C_{f,equ}$ is a time-related variable.

Second, to simplify the description of the correlation between actual furniture and equivalent furniture, a new parameter β is proposed to couple $C_{f,equ}$ and $C_{f,cal}$, as shown in Eq. (12):

$$C_{f,equ} = c_f \times m_f \times \beta = C_{f,cal} \times \beta \quad (12)$$

Note that $C_{f,cal}$ is a constant for a given set of furniture and is the product of the specific heat capacity of the main material c_f and the mass of the furniture m_f; therefore, β is a time variable.

Third, a proposed parameter $A_{f,eff}$ characterizes the effective area of the equivalent furniture in the "Effective Area" method and is defined as the ratio of $A_{f,equ}$ to β: $A_{f,eff} = A_{f,equ}/\beta$.

Dividing Eq. (11) by β, we can obtain Eq. (13):

$$\alpha_f q_{solar} A_{f,eff} + h_{f,rad}\left(T_{f,ave} - T_{ave}\right) A_{f,eff} + \eta_f q_{in,rad} A_{f,eff} = h_f\left(T_{f,ave} - T_{in}\right) A_{f,eff} + C_{f,cal}\frac{dT_{f,ave}}{dt} \quad (13)$$

Here, $A_{f,eff}$ is the only unknown parameter of the effective furniture because the heat capacity of the furniture's main material can be obtained according to reference [26]; the furniture quality can also be obtained from the manufacturer or the manual.

The furniture calculation area $A_{f,cal}$ is defined as a function of the furniture's mass m_f, density ρ_f and size dimension L_f, which is calculated using Eq. (14):

$$A_{f,cal} = \frac{m_f}{\rho_f \cdot L_f} \quad (14)$$

where ρ_f is the density of the furniture main material and L_f is the size dimension, which is calculated as half of the thickness of the main material.

The parameter γ is defined as the ratio of the effective furniture area to the calculation furniture area, as shown in Eq. (15):

$$\gamma = \frac{A_{f,eff}}{A_{f,cal}} \quad (15)$$

For a given piece of furniture, the quality, size dimension and density of the furniture's main material and specific heat capacity are all available. Accordingly, in the heat transfer process between the furniture and indoor air, γ is the only unknown parameter.

It is noteworthy that there are two groups of parameters used above: $C_{f,equ}$ and $A_{f,equ}$. $C_{f,cal}$ and $A_{f,eff}$ ($\gamma A_{f,cal}$) are shown in Fig. 3. The relative calculation processes below continues to use the corresponding relationship. In Fig. 3, $C_{f,cal}$ and $A_{f,cal}$ are the parameters that can be easily calculated from the available parameters, but they do not have a corresponding relationship. As mentioned above, there are no universal equations or methods to obtain $C_{f,equ}$ and $A_{f,equ}$, which depend on the user's experience. Therefore, the new parameters $C_{f,cal}$ and $A_{f,eff}$ ($\gamma A_{f,cal}$) are proposed in this paper to convert all of the uncertain factors into a conversion coefficient γ. Fig. 3

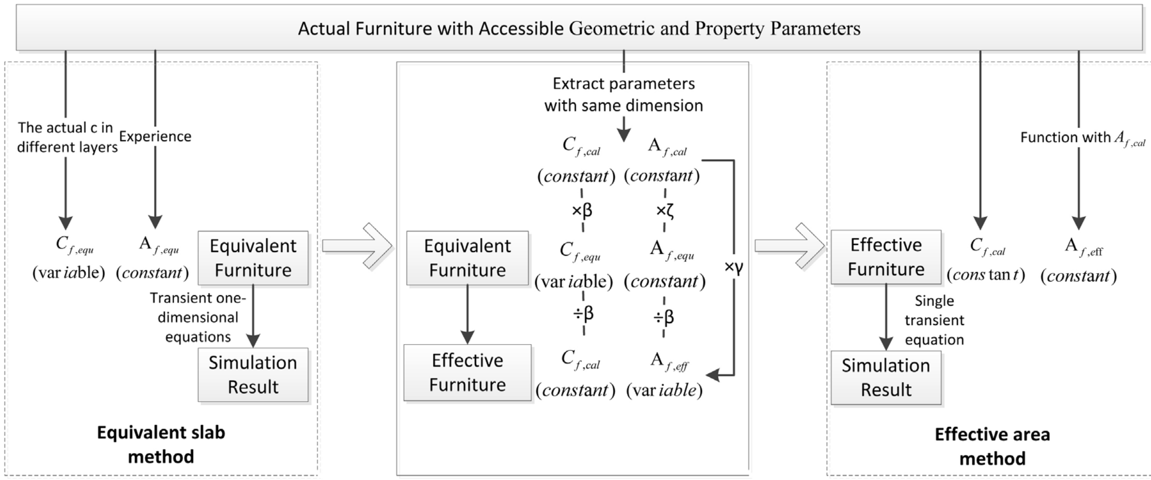


Fig. 3. Outline of the present study.

shows the outline of the present study, which is divided into two key parts. First, in Section 3.1 and 3.2, β, the ratio of $C_{f,equ}$ to $C_{f,cal}$, is validated to be constant to simplify the calculation process. The negligible deviation of the error analysis in Section 3.2 warrants a simplification; thus, a set of transient one-dimensional equations can be substituted by a single transient equation. Therefore, the conversion coefficient γ is considered to be a constant (see the middle part of Fig. 3) under a given condition. Then, Section 4 obtains the recommended value of γ under different furniture distribution density levels and presents the relationship between γ and the furniture distribution density through experiments.

3. Methodology

3.1. "Effective area" vs "Equivalent slab"

Generally, in the "Equivalent Slab" method, irregular furniture is transformed into a slab with a certain thickness, and transient one-dimensional heat transfer is adopted to analyze the dynamic heat transfer characteristics of the furniture. The "Equivalent Slab" method is commonly used and considered accurate in the sense that most furniture are flat; the transient one-dimensional heat transfer method allows for temperature non-uniformity in the thickness direction. Nevertheless, the uncertainty of the conversion coefficient that is obtained according to experience limits further improving its accuracy. In the DR process, emphasis is placed on the accurate description of instantaneous indoor temperature rather than the temperature distribution inside the furniture. Accordingly, the proposed "Effective Area" method assumes that the distribution of temperature along the thickness direction can be ignored; therefore, the lumped parameter method is used to describe the heat transfer between the furniture and air.

Assuming that the equivalent furniture has a uniform temperature, the "Effective Area" method employs an effective heat capacity to calculate the change in the furniture average temperature and the heat transfer with air. In this way, the heat transfer process is described by one differential equation of time, and the unknown parameters can be lumped into a single parameter γ that reflects the relationship between the elements of the effective furniture and the actual furniture (see Fig. 3). Furthermore, the conversion function can be acquired, solving the key problem of the "Equivalent Slab" method.

Although the "Equivalent slab" method is accurate in solving the equations, the error arising from transforming the actual furniture to equivalent furniture significantly affects the whole procedure.

In a nutshell, the "Effective Area" method focuses on the major error and neglects the minor error, i.e., the error caused by ignoring the temperature distribution within the furniture, to simplify the procedure and to control the accuracy to a reasonable level.

The difference between the two methods is presented in Table 1 in detail. The dynamic heat transfer equations of each method are the same as that shown in Eq. (11) and Eqs. (7)–(9). The heat transfer between the furniture and indoor air is calculated using Eq. (16) in the "Effective Area" method and Eq. (17) in the "Equivalent Slab" method.

3.2. Error in simplification

3.2.1. Theoretical analysis

In this study, the effective capacity is used in the proposed "Effective Area" method to describe the thermal storage characteristic of the furniture, and the lumped method is used in the internal conduction analysis. According to Section 2.3 (Lumped Parameter Method) found in chapter 3 of reference [27], only when the Biot number is smaller than 0.1 (shown in Eq. (18)) can the temperature be calculated by the lumped parameter method. Under that condition, the temperature difference between the middle and surface of the slab is less than 5%, and the internal temperature distribution can be assumed to be uniform.

$$\mathrm{Bi} = \frac{h_f \sigma_f}{\lambda_f} < 0.1 \tag{18}$$

For a given material, the heat conduction coefficient λ_f is known. Appendices 7 and 8 of reference [27] recommend the density, heat conduction coefficient, specific heat capacity and heat storage coefficient of different materials. For example, the heat conduction coefficient of plywood, a commonly used material in furniture, is 0.17 W/(m K) [27]. The coefficient of convective heat transfer between indoor air and horizontal plywood is approximately 8.7 W/(m^2 K) according to experience. Appendix B of reference [28] shows some recommend values.

$$\sigma_f < 0.1 \times \frac{\lambda_f}{h_f} \approx 0.1 \times \frac{0.17}{8.7} = 0.002\mathrm{m} \tag{19}$$

According to the Biot criterion, only when the Biot number is smaller than 0.1 can we obtain accurate results using the lumped method; therefore, the thickness of the equivalent furniture must be less than 2 mm, as shown in Eq. (19), and the other materials have similar requirements. However, through surveys and measurements of 100 tables, 20 cabinets and 100 chairs in the researchers' office and other offices in the building, it was found

Table 1
The difference between "Effective Area" method and "Equivalent Slab" method.

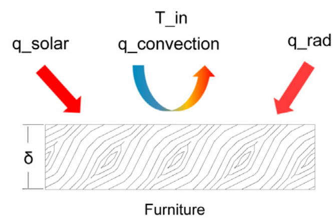
<table>
<tr><th>Method</th><th>"Effective Area" method</th><th>"Equivalent Slab" method</th></tr>
<tr><td>Heat transfer process</td><td>


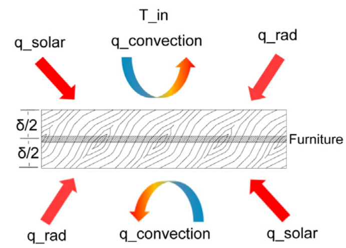
Fig. 4 Heat transfer process of "Effective Area" method</td><td>


Fig. 5 Heat transfer process of "Equivalent Slab" method</td></tr>
<tr><td>Dynamic heat transfer equation(s)</td><td>Same as Eq. (11)</td><td>Same as equations (7)–(9)</td></tr>
<tr><td>Heat transfer with air</td><td>$Q_f = h_f \left(T_{f,ave} - T_{in}\right) A_{f,eff}$ (16)</td><td>$Q_f = h_f \left(T_f - T_{in}\right) A_{f,equ}$ (17)</td></tr>
<tr><td>Characteristics</td><td>1) Differential equation of time
2) The average temperature and area of effective furniture are used to calculate the heat transfer with air
3) A clear functional relationship between the effective furniture area and the actual furniture area; all of the input parameters are the physical parameters of the main furniture material of the
4) Variable $C_{f,equ}$replaces constant $C_{f,cal}$; the deviation in the process can be offset by γ</td><td>1) Differential equations of time and space
2) The surface temperature and area of the equivalent furniture are used to calculate the heat transfer with air
3) No clear functional relationship between the equivalent furniture area and the actual furniture area; users have to obtain equivalent furniture parameters according to experience</td></tr>
</table>

that the slabs forming the furniture are mostly (more than 80%) 20–30 mm, so most of furniture cannot meet the conditions of the lumped method, which explains the deviation between using the "Effective Area" method and the "Equivalent Slab" method.

3.2.2. Case study

A single story room is introduced here to verify the invariance of β, which is the ratio of $C_{f,equ}$to$C_{f,cal}$. The room is composed of three exterior walls and an interior wall with the detailed parameters presented in Table 2. The office is made of steel studs and fire resistant insulation walls. The building is lightweight architecture that has a relatively small thermal lag [29]. The area of the equivalent furniture is approximately 20 m^2. Under this condition, the thermal lag caused by the furniture plays an important role in this room.

In section 2.2, when β is first introduced, it is defined as a time variable. In the "Effective Area" method, to lump the conversion relationship between the actual and equivalent furniture into a constant coefficient, β is assumed to be constant. Thus, $C_{f,equ}$ and $A_{f,equ}$ are converted into $C_{f,cal}$and $A_{f,eff}$, respectively, and the conversion relationship between the actual and equivalent furniture is simplified into a constant proportionality coefficient (i.e., γ) between $A_{f,eff}$ and A_{cal}. A typical situation is introduced below to verify the accuracy of neglecting the variability of β by testing the effects of assuming that β is constant.

The outdoor air temperature can be assumed to be a harmonic function of time with angular frequency ωand amplitude $A_{T_{out}}$, i.e. the difference between the maximum value and the average value of T_{out}, as shown in Eq. (20) [23]. According to this reference, 30 °C is the average temperature of the research area (the average summer temperature in Shanghai); 5 °C is the outdoor temperature amplitude; and the peak temperature appears at 15:00. What should be noticed is that in this case, the impact of solar radiation is ignored for simplification. T_{out} denotes outdoor dry bulb temperature in Eq. (20).

$$T_{out} = 30 + 5 \cdot \cos(\omega(\mathrm{t} - 15)) \tag{20}$$

The coefficient of convective heat transfer is easily obtained according to experience. The ventilation air flow rate is considered to be constant. The heat source and all radiation heat transfer factors are neglected because during DR events, these values can be assumed to be constant for the short time period.

In this case, the two methods are used in the simulation of an office, as shown in Fig. 3, and the relative error between the "Effective Area" method and the "Equivalent Slab" method is discussed for different thickness of "furniture".

The dynamic heat transfer equations of the room are shown in Table 3. The heat balance model of furniture is shown in Eq. (21) for the "Effective Area" method and is described by Eqs. (13), (14) and (22) for the "Equivalent Slab" method. The envelope balance model in this simulation is converted into Eqs. (3), (4) and (23). The heat balance model of the internal partitions is shown in Eqs. (24)–(26). The thermal energy balance equation of the indoor air is shown in Eq. (27). These two sets of equations are solved using the finite difference method with the implicit difference scheme. The whole day (24 h) is divided into 150 time steps. Then, the Gauss iterative method is applied to solve the discretized equations. The computational process are realized by Matlab. The accuracy of the "Effective Area" method is analyzed by three indicators: $\delta_{T_{in}}$, the greatest relative error of the indoor temperature, δ_{ν_T}, the relative error of the decrement coefficient, and δ_{ξ_T}, the relative error of the time lag. The upper acceptable limit of the relative error in this research is 10%. Section 3, Chapter 5 of reference [27] shows detailed information about the decrement coefficient ν_T and time lag ξ_T.

(1) The greatest relative error of the indoor air temperature

$\delta_{T_{in}}$ is the greatest relative error of the indoor air temperature of the "Effective Area" method (subscript 1) and the "Equivalent Slab method" (subscript 2) in all time steps to estimate whether the temperature deviation of the "Effective Area" method is within the acceptable range, which is calculated as shown in Eq. (28):

$$\delta_{T_{in}} = \max_{0 \le t \le t_{end}} \left(abs\left(\left(T_{in,1}(t) - T_{in,2}(t) \right) / T_{in,2}(t) \times 100\% \right) \right) \tag{28}$$

(2) The relative error of the decrement coefficient

The indoor temperature decrement coefficient is defined as the ratio of the outdoor temperature amplitude $A_{T_{out}}$ to the indoor tem-

Table 2
Parameters of the "office room".

Components	Type	Geometric parameters		Property parameters [27]			
		Area(m^2)	Thickness(m)	Material	Density (kg/m^3)	Heat conduction coefficient (W/(m·K))	Specific capacity (kJ/(kg·K))
East wall	Envelope	14.94	0.17	Steel stud + Insulation panel	150	0.045	1.22
West wall	Internal partition	14.94	0.17	Steel stud + Insulation panel	150	0.045	1.22
South wall	Envelope	7.07	0.17	Steel stud + Insulation panel	150	0.045	1.22
North wall	Envelope	8.58	0.17	Steel stud + Insulation panel	150	0.045	1.22
South window	External window	3.40	–	Monolayer white glass	2500	0.76	0.84
North door	Outside door	1.89	–	Aluminum alloy	2700	203	0.92
Ceiling	Ceiling	14.89	–	Gypsum board	1050	0.33	2.01
Floor	Raised flooring	14.89	–	Steel	7850	58.2	0.48
Furniture	Internal mass	20	0.002–0.030	Plywood	600	0.17	2.51

Table 3
Transient heat transfer equations of "office room".

Equations	"Effective Area" method	**"Equivalent Slab" method**
Furniture	$h_f\left(T_{f,ave}-T_{in}\right)A_{f,eff}+C_{f,cal}\dfrac{dT_{f,ave}}{dt}=0$ (21)	Same as (13) (14) $-\lambda_{f,\frac{\sigma_f}{2}}\left(\dfrac{\partial T_f}{\partial x_f}\right)_{x_f=\frac{\sigma_f}{2}}=h_f\left(T_{f,\frac{\sigma_f}{2}}-T_{in}\right)$ (22)
Envelope	Same as (3) (4) $\lambda_e\left(\dfrac{\partial T_e}{\partial x_e}\right)_{x_e=\sigma_e,}=h_{e,in}\left(T_{in}-T_{e,in}\right)$ (23)	
Internal partitions	$\dfrac{\partial T_p}{\partial t}=a_p\dfrac{\partial^2 T_p}{\partial {x_p}^2}0\le x_p\le\sigma_p/2, t>0$ (24) $-\lambda_{p,0}\left(\dfrac{\partial T_p}{\partial x_p}\right)_{x_p=0}=0$ (25) $-\lambda_{p,\frac{\sigma_p}{2}}\left(\dfrac{\partial T_p}{\partial x_p}\right)_{x_p=\frac{\sigma_p}{2}}=h_p\left(T_{p,\frac{\sigma_p}{2}}-T_{in}\right)$ (26)	
Thermal energy balance equation of indoor air	$\rho_a v_a c_a\dfrac{\partial T_{in}(t)}{\partial t}=\sum_e Q_e(t)+\sum_p Q_p(t)+\sum_f Q_f(t)+\sum Q_{inf}(t)$ (27)	

perature amplitude $A_{T_{in}}$, as shown in Eq. (29) [27], and the relative error of the decrement coefficient is shown in Eq. (30).

$$\nu_T=\frac{A_{T_{out}}}{A_{T_{in}}} \tag{29}$$

$$\delta_{\nu_T}=abs\left(\frac{\left(\nu_{T,1}-\nu_{T,2}\right)}{\nu_{T,2}}\times 100\%\right) \tag{30}$$

(3) The relative error of the time lag

The time lag characterizes the delay between the peak or trough time difference between the indoor temperature and outdoor temperature, as shown in Eq. (31) [27]. The relative error of the time lag δ_{ξ_T} is shown in Eq. (32).

$$\xi_T=t_{in}^{max}-t_{out}^{max}ort_{in}^{min}-t_{out}^{min} \tag{31}$$

$$\delta_{\xi_T}=abs\left(\frac{\left(\xi_{T,1}-\xi_{T,2}\right)}{\xi_{T,2}}\times 100\%\right) \tag{32}$$

From Fig. 6 , it can be observed that when the thickness of the equivalent furniture is equal to 2 mm and meets the conditions of the lump method, the three factors are all smaller than 0.01%. Moreover, they are no greater than 2.5% even when the thickness of the equivalent furniture reaches 30 mm. (The largest relative error is that of the decrement coefficient, which is equal to 2.14%). Fig. 7 shows the comparison of the indoor air temperature with the two methods when σ_f equals 30 mm. Although the relative error of the decrement coefficient increases rapidly with increasing thickness, it is only 2.14% when the thickness is approximately 30 mm. This relative error of the decrement coefficient reaches 10% when the thickness is more than 100 mm, whereas the relative errors of the other two criteria are still less than 10%. In a nutshell, the errors are negligible, and β can be considered constant.

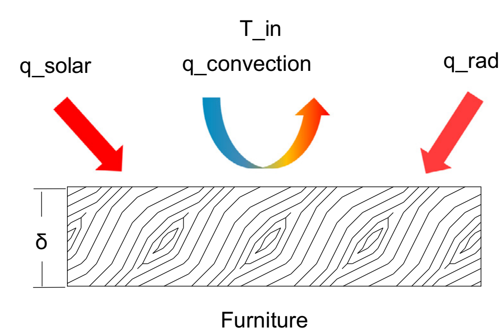


Fig. 4. Heat transfer process of "Effective Area" method.

For example, assuming that σ_f equals 30 mm, the calculation process for the above three indicators is shown in Table 4. The first eight parameters are obtained from the model, which are necessary when calculating the three indicators.

4. Experimental study

The "Effective Area" method aggregates all of the conversion relationships between the actual and effective furniture into a conversion coefficient between the calculated area and effective area. The coefficient is an empirical value that can be obtained experimentally. To determine the common values of the coefficient, several sets of experiments are conducted under different typical office furniture settings.

Table 4
Sample calculation of $\delta_{T_{in}}$, δ_{ν_T}, and δ_{ξ_T} when σ_f equals 30 mm.

Parameter	Explanation		Value
$T_{in,1}(t)$	The indoor temperature of each time step with effective area method (method-1)		30.36, 30.36, 30.32. . ., 31.18, 31.18, 30.36 (°C)
$T_{in,2}(t)$	The indoor temperature of each time step with slab method (method-2)		30.35, 30.35, 30.32. . .31.11, 31.13. . ., 30.35 (°C)
$A_{T_{out}}$	The difference between the maximum and average temperature	Outdoor	5.12 (°C)
$A_{T_{in},1}$		Indoor under method-1	1.30 (°C)
$A_{T_{in},2}$		Indoor under method-2	1.25 (°C)
t_{out}^{max}	The time when the temperature reaches the peak	Outdoor	15:22
$t_{in,1}^{max}$		Indoor under method-1	19:11
$t_{in,2}^{max}$		Indoor under method-2	19:11
$\delta_{T_{in}}$	max(*the relative error of each time step*)		0.2%
δ_{ν_T}	–		2.14%
δ_{ξ_T}	–		0%

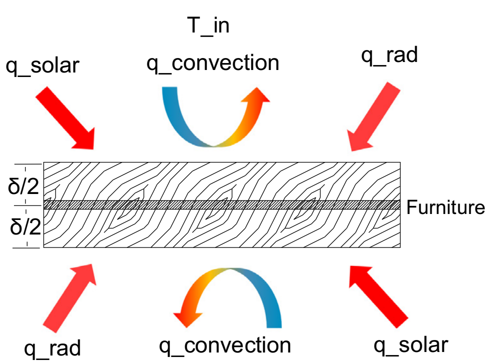


Fig. 5. Heat transfer process of "Equivalent Slab" method.

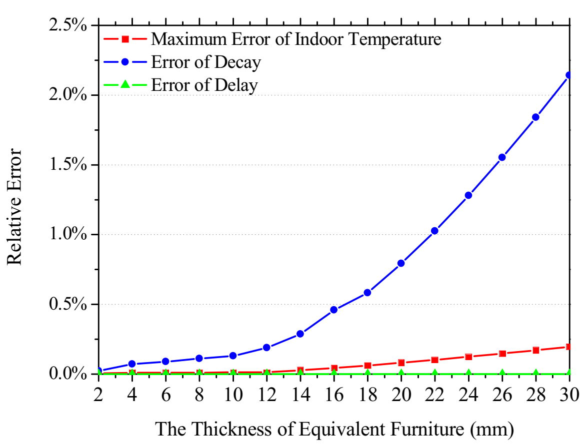


Fig. 6. Variation of the three factors under different furniture thicknesses.

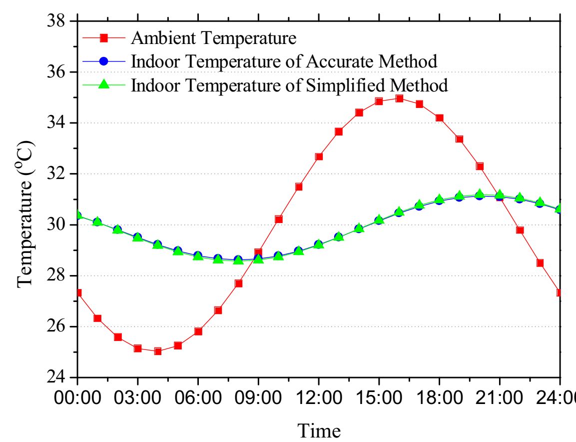


Fig. 7. Comparison of the indoor air temperature using two methods ($\sigma_f = 0.03m$) a) Top view of test platform b) Profile of test platform.

4.1. Test platform

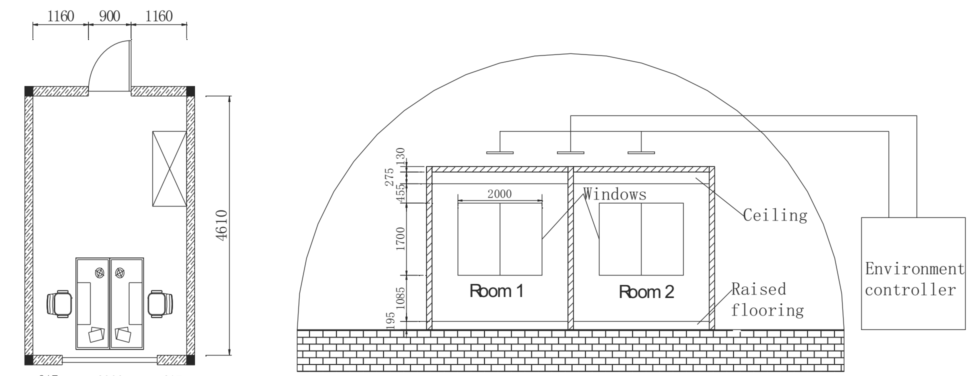
The experimental platform is the east room of the "Building Energy Efficiency Laboratory" (Fig. 8(a)), room 2, located in Shanghai, China. The configuration and size of the test room are shown in Fig. 8. The net area of each component is shown in Table 2. The entire test platform is located inside a chamber. The environmental parameters of the chamber can be adjusted according to the experimental requirements, and the ambient environment of the test room is controllable.

4.2. Experimental setup

To minimize the uncertainty of the ambient environment on the experimental accuracy, the external shades of the chamber are closed to prevent solar radiation. During the experiments, the HVAC systems are kept off, and other internal heat sources are also turned off to eliminate their influence on the accuracy of the experiments. The thermal inertia is a physical characteristic of the building itself that does not change with the variation of the outdoor and indoor environments. The experiments collect the indoor air temperature of the test room and the air temperature of the chamber (i.e., ambient temperature) every minute.

The test room is arranged as an office. The floor space of the office is approximately 16 m^2. According to clause 4.2.3 of the *Design Code for Office Buildings* [30], the per capita area for an office should not be less than 4 m^2, so the office can accommodate at most four people. To acquire the conversion coefficients of different furniture densities, several experiments were conducted under five different scenarios, as shown in Table 5. Scenario 1, vacancy, means that the office is empty. Scenarios 2 through 5 represent the room being used as an office for 1–4 people. The weights of the furniture, desk, chair, file and file cabinet are weighted by a platform scale before the experiment. Usually, one person has a desk and a chair, but the weight of the file and the number of file cabinets for each people are not common. Therefore, the researchers surveyed 10 offices in their office building to weigh the files for each person and count the number of file cabinets for each people. The numbers in Table 5 are the average numbers from the survey.

The experiments of different scenarios are divided into two groups, i.e., a training group and a validating group. Scenario 1 is used to verify the dynamic thermal model of the office without furniture. In the training group, the input condition is the ambient temperature; the output is indoor air temperature; and the adjustable parameters are the physical properties of the construction materials. The physical properties are tuned within the recommended range [27] to make the output of the building model



a) Top view of test platform b) Profile of test platform

Fig. 8. Test platform.

Table 5
Descriptions of the office under five different scenarios.

No.	Description	Furniture Density Level			
		Desk	Chair	File	File Cabinet
		main material: plywood weight: 48 kg	main material: plywood weight: 12 kg	main material: paper	main material: plywood weight: 30 kg
1	vacancy	0	0	0	0
2	1 people office	1	1	45 kg	1
3	2 people office	2	2	85 kg	1
4	3 people office	3	3	120 kg	2
5	4 people office	4	4	150 kg	2

Table 6
The accuracies of the building thermal model and the recommended conversion coefficients.

Scenario	Per Capita Area (m^2)	Maximum Error						Conversion coefficient
		Training group			Validating group			
		Temperature Deviation (°C)	Decay Factor	Delay (min)	Temperature Deviation (°C)	Decay Factor	Delay (min)	
Vacancy	–	0.42	2.16%	0	0.42	0.80%	−9	–
1	16	0.37	1.57%	−2	0.34	2.49%	0	0.60–0.75
2	8	0.38	2.11%	−10	0.48	2.16%	8	0.38–0.50
3	5.3	0.34	1.56%	−9	0.39	4.73%	0	0.25–0.35
4	4	0.34	0.83%	3	0.48	0.67%	−5	0.15–0.25

comparable to the experimental results. The errors meet the following requirements: 1) the temperature deviation for each time step is less than 0.5 °C, which is a small deviation for comfortable air-conditioning area [31]; 2) the relative error of the decrement coefficient is less than 5%; and 3) the time lag is less than 10 min. The purpose of the model introduced in this paper is to accurately describe the indoor temperature. Therefore, it can monitor whether the indoor temperature exceeds the comfort range during DR events. As mentioned above, less than 10% is defined as the acceptable relative error in this research. A DR event usually lasts more than 2 h, so the time lag should less than 12 min; 10 min is selected in requirement 3).

Then, the input condition changes to the ambient temperature of the verification group. The trained model is accurate if the outputs of the verification group, i.e., the indoor air temperature, also satisfy the above three criteria. Scenario 1 is the benchmark scenario. In scenarios 2–5, the dynamic thermal equations of the furniture were added into the model of scenario 1. Scenarios 2–5 collect the indoor air temperature under different furniture distribution densities. The training and verification processes is similar to that of Scenario 1. The furniture effective area is described by Eq. (15), and the unknown parameter is the conversion coefficient of the effective area. The coefficient is adjusted from 0 to 1 to make the output errors of the building model comparable to the experimental results and to ensure that the errors meet the above three criteria. The detailed calculation process of the converted coefficients is shown by the flowchart below (Fig. 9).

4.3. Results and discussion

Through training and validation, all of the dynamic thermal models of the office reach the accuracy criteria in the five scenarios. The representatives of the training and validation groups are shown in Fig. 10. Table 6 shows the maximum errors of the training and validation groups under different scenarios. The model errors meet the criteria, and the temperature deviation varies within 0.34–0.48 °C. Criterion 1 is used to control the maximum temperature deviation but cannot describe the distribution of the deviations. Therefore, through further analyzing Fig. 10 by comparing the test and simulation results of the indoor temperature, the obvious deviation

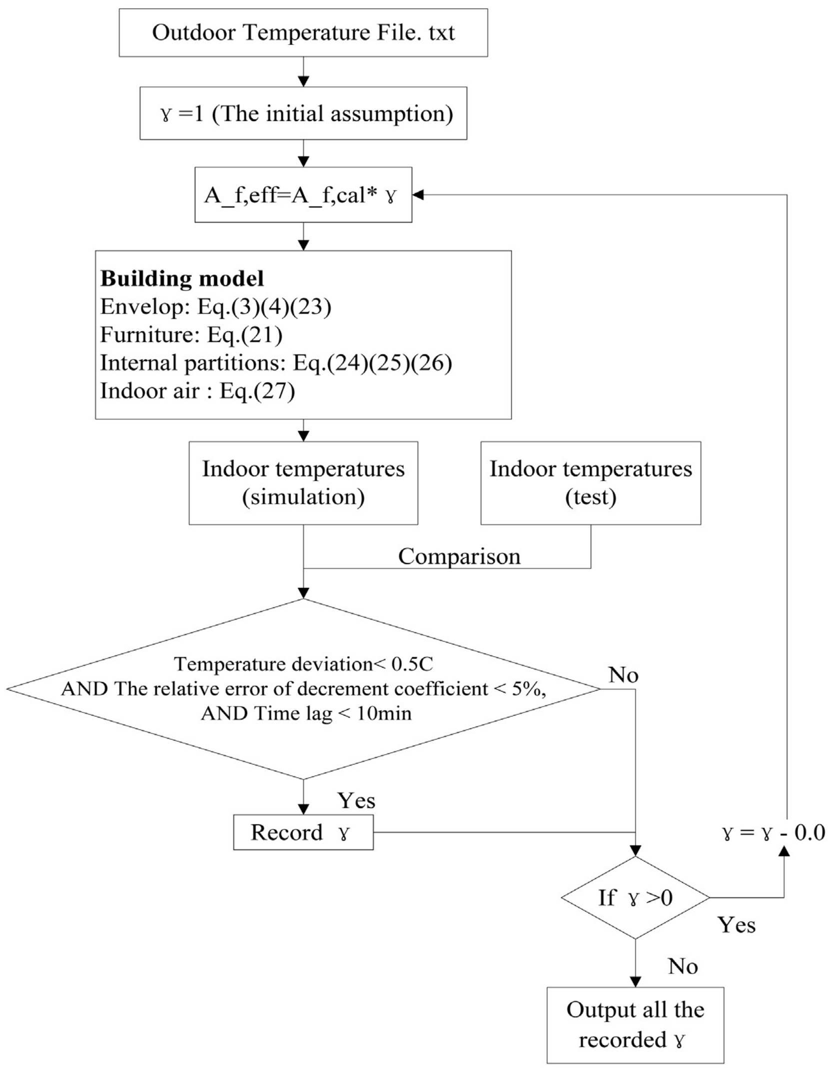


Fig. 9. The detailed calculation process of the converted coefficients.

of temperature accounts for only a small proportion of the whole indoor air curve. In the DR studies of HVAC systems, the focus is on controlling the indoor air temperature to not exceed the comfort range when DR strategies, such as indoor temperature reset and shutting down a portion of the chillers to reduce peak load, are implemented. In particular, from 12:00–18:00, when the DR event of the HVAC system most likely occurs, the model results match the experimental results well.

In Scenarios 2–5, the furniture consists of various objects with different forms and materials. In this research, the conversion coefficient of the effective area is considered as a uniform integrated value for all of the furniture. As the experimental and theoretical calculations show in Table 6, the accuracy of the building thermal model is not sensitive to the conversion coefficient, and the coefficient varying within a certain range would not significantly influence the accuracy of the building model.

From Table 6, it is obvious that there is a negative correlation between the conversion coefficients and furniture density. Because it is convenient to select the corresponding coefficient according to the per capita area in buildings, the functional relationship between per capita areas and conversion coefficients is analyzed further, as shown in Fig. 11, which presents a significant linear relation.

It can be concluded that the conversion coefficient of the effective area is mainly influenced by the furniture distribution density; therefore, it is could be inferred that the coefficients obtained in this research are universal to some degree. For other office buildings, the coefficient can be selected according to the per capita area. For other building types, the coefficient can also be obtained by comparing their furniture situations to our experimental scenarios. The coefficient is not sensitive to the furniture distribution density, which is a varies under different density levels; therefore, it is can be inferred that when the furniture distribution density varies slightly, using the original conversion coefficient may not influence the accuracy of the results. Regarding the application, the coefficient can be selected according to the general statistical results of the indoor furniture. However, these inferences need more field tests in different situations for further validation.

5. Conclusions

In the field of building DR research, it is important to accurately describe the characteristics of building thermal mass with simulation models. Unlike building envelopes and partitions, the internal thermal mass (such as furniture) has irregular shapes and random distributions. Therefore, the internal thermal mass needs a simplified and accurate method to calculate its thermal effects when analyzing the dynamic thermal behavior of a whole building during DR events. Because the control objective is the indoor

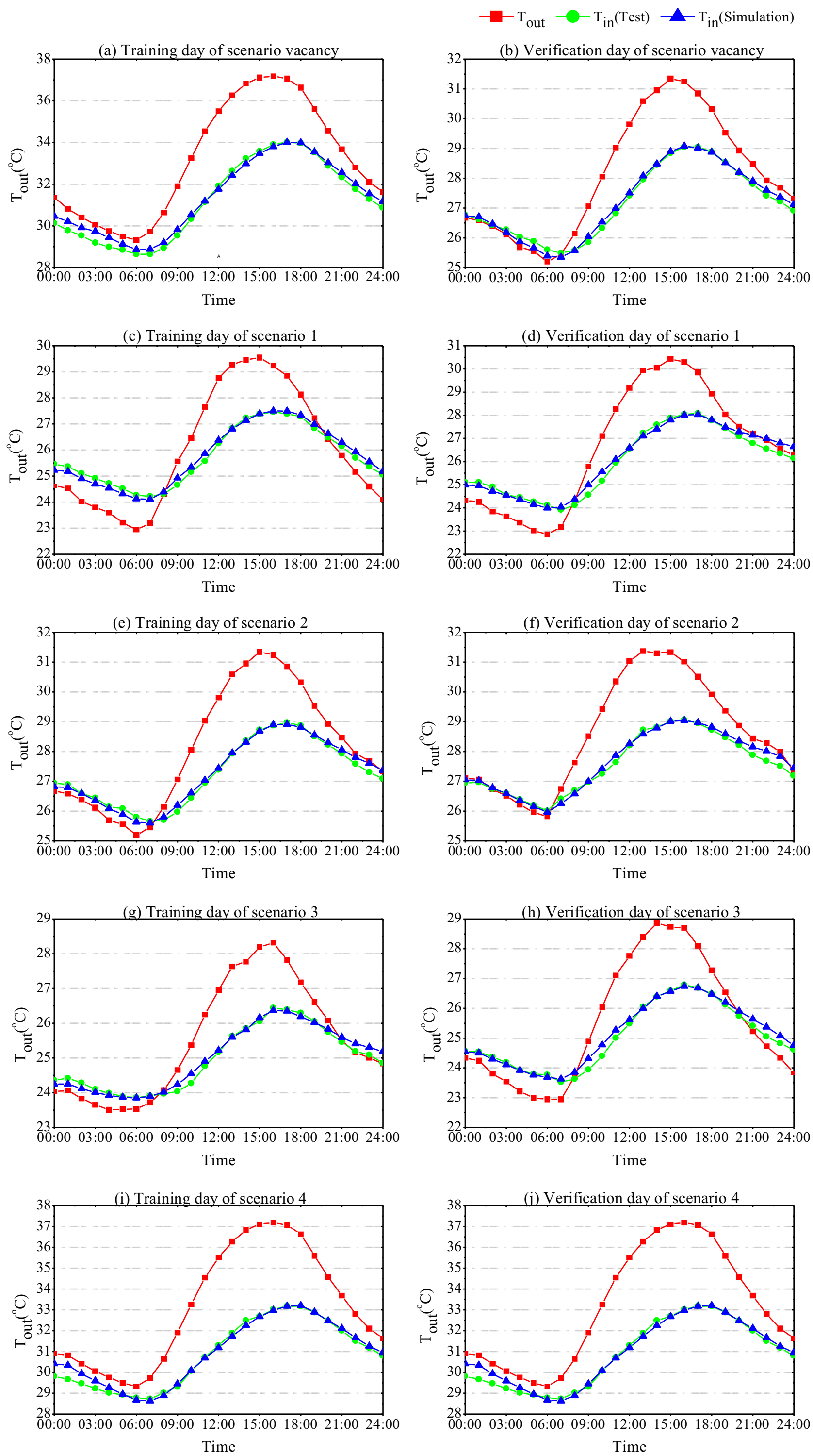


Fig. 10. Representative days of the training and verification groups under different scenarios.

air temperature, it is not necessary to describe the temperature distribution inside the furniture. This research provides a new method called the "Effective Area" method for dynamic thermal behavior analyses of irregular internal mass through simplification of furniture with one-dimensional temperature gradients. The new method solves the conversion problem between actual furniture and equivalent furniture. The parameters of the conversion functions can be calculated from some easily available furniture parameters. This method considers all of the thermal relationships associated with internal mass, such as the relationship between the effective thermal capacity of furniture and the specific heat of its main material and the relationship between the calculation area and the equivalent area. Then, the method combined these calculations into a single conversion process of effective area. This paper provides the conversion coefficients for different furniture densities based on the experimental and theoretical

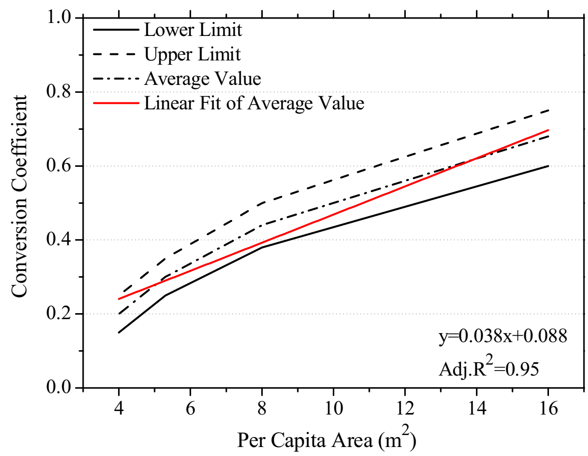


Fig. 11. The functional relationship between per capita areas and conversion coefficients.

calculation results. The significance of this research is listed as follows:

- When the equivalent furniture does not satisfy the conditions of the lumped parameter method (Biot number <0.1), assuming that the temperature of the furniture is uniform does not significantly affect the accuracy of the dynamic thermal model at the whole building level.
- A linear relation exists between the conversion coefficient of the effective area and the furniture distribution density, so the coefficient is a function of the furniture density.
- For a given furniture distribution density, the coefficient varies within a certain range that does not influence the accuracy of the whole building thermal model.
- Based on the above two points, the conversion coefficients presented in this paper can be extrapolated and can be applied in a way that users can select the corresponding number according to the furniture distribution density.

The "Effective Area" method solves the conversion problem between actual furniture and equivalent furniture, thus improving the accuracy of building thermal models. Building performance simulation software such as EnergyPlus and TRNSYS can use this method to improve their current calculation algorithm for building internal mass.

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