An Analysis of the Hybrid Internal Mass Modeling Approach in EnergyPlus

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Abstract

Accurate simulation of building system dynamics is particularly important for understanding building energy flexibility. Among all dynamics in a building, a zone temperature's variation is especially important, as it significantly affects a building's electricity load profile when its heating, ventilating, and air conditioning (HVAC) system is controlled with on/off cycles or setpoint reset strategies. To accurately simulate a zone temperature's dynamics, internal mass needs to be modeled carefully. In this paper, we compare the two internal mass modeling approaches provided by EnergyPlus, i.e., internal mass object and zone air capacitance multiplier, to better understand their impacts on zone temperature simulation. Real building zone temperature dynamic data from small- and medium-sized office buildings are analyzed and compared with simulated data. In particular, we illustrate the effectiveness of a hybrid method of the two EnergyPlus modeling approaches, which yields more realistic zone temperature dynamics, especially when the zone is conditioned with heat pump systems with on/off cycling.

Introduction

With the increased adoption of renewable energy and smart grid, it is important to improve the flexibility of both the supply-side and demand-side of an electric grid to meet the needs of power generation, transmission, distribution, and dispatch. As one of the main users of the electric grid, the building sector (including both residential and commercial) plays an important role in the realization of a flexible grid. Fully exploiting the energy flexibility potential of buildings and building equipment can effectively achieve the goals of reducing energy costs, shifting electricity peaks, increasing renewable energy use in the sector, and enhancing the stability of the grid.

Accurate simulation of building system dynamics is particularly important for understanding building energy flexibility. Among all dynamics in a building, zone temperature variation is especially important, as it can significantly affect a building's electricity load profile when the heating, ventilating, and air conditioning (HVAC) system is controlled with on/off cycles or setpoint reset strategies to achieve load flexibility (Cetin et al., 2019). To accurately simulate zone temperature dynamics, the effect of internal mass (e.g., furniture) needs to be modeled carefully.

EnergyPlus (Crawley et al., 2001) is a widely used whole building energy simulation program that can calculate building heating and cooling loads and energy consumption. It provides two internal mass modeling approaches (U.S. Department of Energy, 2020b): (i) specify internal mass as internal surfaces that participate in radiative and convective heat exchanges using the InternalMass object (in which the internal mass area and material are specified) and (ii) specify internal mass by changing zone air capacitance using the temperature capacity multiplier of the ZoneCapacitanceMultiplier:ResearchSpecial object. These two approaches have been discussed in several studies. Raftery et al. (2014) assessed the impact of furniture and contents (i.e., internal mass) on the zone peak cooling loads. They performed 5400 parametric simulation runs to show how the parameters specified in the InternalMass object affect peak cooling load. Through this approach, the peak cooling load is found to be changed by a median value of -2.28 % across the studied parameter space. Lee and Hong (2017) introduced an inverse algorithm for the determination of the temperature capacity multiplier to reflect different amounts of internal mass. HVAC system operational data as well as detailed zone measurements, such as zone surface temperatures, infiltration air flow rates, and internal heat gains, are used for the determination of the multiplier. They suggested multipliers 3-6 for light offices, 6-10 for typical offices, and 10-15 for heavy mass offices. Cetin et al. (2019) employed both internal mass modeling approaches in their development and validation of an HVAC on/off controller using EnergyPlus for energy simulation of residential and small commercial buildings. The parameters used in the InternalMass object were adopted from the Building America House Simulation Protocols and a value of 3.6 for temperature capacity multipliers was determined through trial and error by comparing the cooling coil cycles of the simulation data and the field-collected data.

Although the two approaches have been widely used in existing studies, there is a lack of insight into the impact of these two approaches on the dynamics of zone temperature, which further affects load profile and energy consumption. In the past, energy simulation models such as EnergyPlus is often used for energy consumption calculations with large timesteps (e.g., hour, or 15-minute) where the fast dynamic is neglected. Consequently, the two different internal mass modeling approaches have received little attention, because the InternalMass object is sufficient to capture the "long-term effect" (which will be further explained in the following sections) of the internal mass in slow dynamics. However, when energy simulation models (i.e.. EnergyPlus), is used for studying the dynamics of a building system, such as load flexibility, systematically understanding how these two internal mass modeling approaches affect zone temperature dynamics is very important.

In this paper, we aim to deepen the readers' understanding of the internal mass modeling approach through heat balance equation analysis, parameter analysis, and numerical experiments, especially for those who use EnergyPlus to simulate the fast dynamics of HVAC systems controlled with on/off cycling and setpoint reset strategies. The insights from this paper will help researchers to select the suitable internal mass modeling approach.

This paper is organized as follows: the heat balance equation of the room is firstly analyzed; the roles of the two internal mass modeling approaches in the heat balance equation are illustrated; the findings presented in the previous analysis are then verified using the example of heat pump on/off control through a numerical experiment; next, dynamic real building zone temperature data from small- and medium-sized office buildings are used to show that the analysis is reasonable; and finally, conclusions and recommendations are summarized.

Zone heat balance equation

Our analysis starts with the fundamental physics-based zone air heat balance equation of EnergyPlus (U.S. Department of Energy, 2020a),

$$C_z \frac{dT_z}{dt} = \sum_{i=1}^{N_{sl}} \dot{Q}_i + \sum_{i=1}^{N_s} h_i A_i (T_{si} - T_z) + \sum_{i=1}^{N_z} \dot{m}_i c_p (T_{zi} - T_z) + \dot{m}_{inf} c_p (T_o - T_z) + \dot{m}_{sup} c_p \left(T_{sup} - T_z\right) \quad (1)$$

Descriptions of the symbols used in this equation can be found in the nomenclature section. The analytical solution (U.S. Department of Energy, 2020a) of the zone air temperature at time t is,

$$T_z^t = \left(T_z^{t-\delta t} - \frac{H}{k_z}\right) e^{-\frac{\delta t}{\tau}} + \frac{H}{k_z} \quad (2)$$

where:

$$H = \sum_{i=1}^{N_{sl}} \dot{Q}_i + \sum_{i=1}^{N_s} h_i A_i T_{si} + \sum_{i=1}^{N_z} \dot{m}_i c_p T_{zi} + \dot{m}_{inf} c_p T_o + \dot{m}_{sup} c_p T_{sup};$$

$$k_z = \sum_{i=1}^{N_s} h_i A_i + \sum_{i=1}^{N_z} \dot{m}_i c_p + \dot{m}_{inf} c_p + \dot{m}_{sup} c_p;$$

$$\tau = \frac{C_z}{k_z}.$$

To facilitate an understanding of the role of the two internal mass modeling approaches, we can treat this equation system as a first-order linear time-invariant system with H/k_z as a constant step input. This system has two important parameters, one is the time constant τ, which governs the speed of the zone temperature transient response, and the other is H/k_z, which is the final steady state temperature. The two internal mass modeling approaches of EnergyPlus capture the effect of internal mass on room temperature dynamics by manipulating one or both of these parameters.

The first approach uses the InternalMass object. This object models the internal mass by defining the construction material of the internal mass and the surface area of the internal mass object. The geometry of the internal mass construction is simplified as it is usually difficult to measure. With this modeling approach, both the time constant τ and the final steady state H/k_z are adjusted. Increasing the surface area, A_i, of the internal mass will lead to an increase in H/k_z and a decrease of τ.

The second approach uses the zone capacitance multiplier. ZoneCapacitanceMultiplier:ResearchSpecial object is an advanced feature to specify the effective thermal storage capacity of a zone. It directly modifies the zone capacitance C_Z , which determines τ, by multiplying it with a temperature capacity multiplier C_T. This approach only modifies the time constant of the transient response and has no impact on the final steady state. An increase in C_z leads to an increase in τ.

Parametric analysis

In this section, the impact of the two internal modeling approaches on zone temperature dynamics are illustrated by adjusting: (i) the surface area, A_i, of the internal mass in the targeted zone and (ii) the temperature capacity multiplier of the targeted zone. In the following subsections, the numerical model and test settings will be introduced first, followed by the parametric analysis.

Numerical model and test settings

The ASHRAE 90.1-2004 small office model from the commercial prototype buildings (U.S. Department of Energy, n.d.), as shown in Figure 1, is selected for the parametric analysis.

To illustrate the effect of the parameters on the simulation, the following simulation settings are used:

- The simulation period is 1- day and the simulation time step is 1-minute.
- All zones are served by ideal load systems.

- Perimeter zones are maintained at 22.22 °C (72 °F) all day.
- Core_ZN HVAC system is shut down at 12:00 noon.

Boundary conditions are set to the following constant values to reduce their dynamic impact:

- Sky temperature is maintained at 23.89 °C (75 °F)
- Solar radiation is set to 0.
- Outdoor air temperature is set to 22.22 °C (72 °F).
- Outdoor air relative humidity is set to 40 %.
- No internal heat gain is added to the zones, except for Core_ZN, in which an internal heat gain of 6.78 W/m^2 from electric equipment is added.

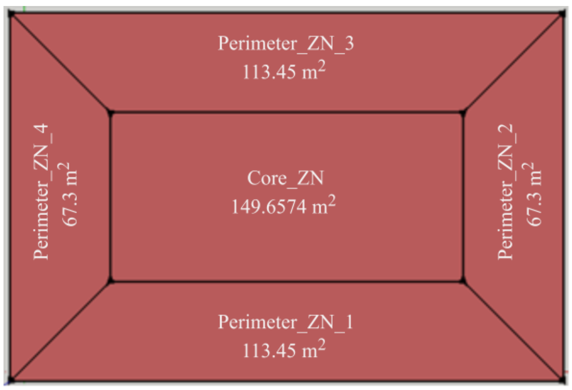

Figure 1: Small office model floor plan.

Zone temperature of the Core_ZN is selected for the investigation, and the results in the following subsections focus on the HVAC shut down period (i.e., 12:00 to 24:00). A closer comparison for zone temperature rise, T_{rise}, over a short period of time (10 minutes) after system shutdown and the difference between the zone temperature at 24:00 and the baseline temperature at 24:00, $T_{z,ss}$-$T_{z,ss,baseline}$, are presented. The baseline case has no InternalMass object specified (i.e., IntMassArea=0) and the zone temperature capacity multiplier is set to 1 (i.e., C_T=1).

Impact of internal mass surface area

In this subsection, four cases with different sizes of internal mass surface area are compared. The four cases are:

- IntMassArea=0 (baseline): empty zone
- IntMassArea=1xFlrArea: same size as the floor area
- IntMassArea=2xFlrArea: 2 times the floor area
- IntMassArea=4xFlrArea: 4 times the floor area

The zone temperature capacity multiplier is set to 1 in these cases. The material properties of the internal mass are summarized in Table 1.

Figure 2 shows the dynamic profile of the room temperature of Core_ZN under these four cases. According to the figure, the size of the internal mass surface area plays a significant role in the final temperature at 24:00. This observation is consistent with our analysis of the heat balance equation as these lines are heading towards distinguishable steady states. Its effect on the initial rate of the temperature variation is very small during the short period after the system shutdown.

Table 1: Internal mass material properties.

Name	Std Wood 6inch
Roughness	MediumSmooth
Thickness	0.15 m
Conductivity	0.12 W/m-K
Density	540 kg/m^3
Specific Heat	1210 J/kg-K
Thermal Absorptance	0.9
Solar Absorptance	0.7
Visible Absorptance	0.7

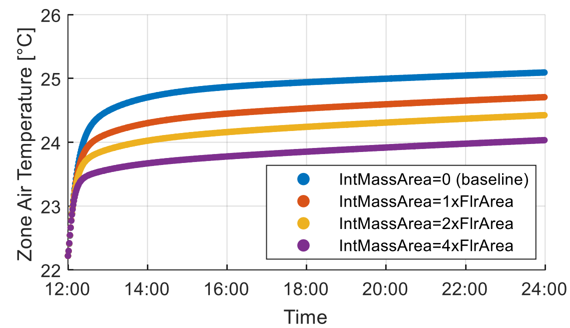

Figure 2: Temperature dynamics of Core_ZN under different sizes of internal mass surface area.

According to the data in Table 2, from a no internal mass scenario (i.e., IntMassArea=0) to a very heavy internal mass scenario (i.e., IntMassArea=4xFlrArea) in the opinion of Raftery et al. (2014), the zone temperature rise 10 minutes after the system shutdown decreases by only 0.13 °C. In other words, the temperature of a zone with heavy internal mass behaves almost the same as the zone temperature in an empty room in the initial transition period.

Table 2: Temperature data comparison under different sizes of internal mass surface area

Case	Mass per area [kg/m^2]	T_{rise} [°C]	$T_{z,ss}$-$T_{z,ss,baseline}$ [°C]
IntMassArea=0 (baseline)	0	1.05	0
IntMassArea =1xFlrArea	81	1.02	-0.39
IntMassArea =2xFlrArea	162	0.98	-0.67
IntMassArea =4xFlrArea	324	0.92	-1.06

Impact of the temperature capacity multiplier

In this subsection, four different temperature capacitance multipliers are compared, i.e., C_T equal to 1 (baseline), 2, 4, and 8. No InternalMass object is specified in these cases. Figure 3 shows the dynamic profile of the room temperature under four different temperature capacitance multipliers. The zone air capacitance plays a significant role in the initial transient period, while in the long run, temperatures with different multipliers converge to a similar state.

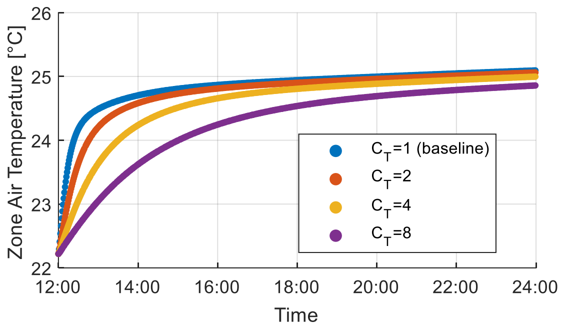

Figure 3: Temperature dynamics under different temperature capacitance multipliers.

Table 3 conveys the same message in numerical form. As the internal mass of the zone increases, the damping of the zone temperature over time increases accordingly. This damping behavior has very important implications for the study of on/off control or control with frequent setpoint changes. These implications are presented in the numerical examples in the next section.

Table 3: Temperature data comparison under *different temperature capacity multiplier.*

Case	T_{rise} [°C]	$T_{z,ss}$-$T_{z,ss,baseline}$ [°C]
C_T=1 (baseline)	1.05	0
C_T=2	0.58	-0.03
C_T=4	0.30	-0.10
C_T=8	0.15	-0.23

Internal mass modeling in on/off control

From the above parametric analysis, we see that the two approaches have very different impacts on the simulation of temperature dynamics. This difference subsequently affects the load and the energy consumption calculations in EnergyPlus. In this section, the impacts of the two approaches are further compared in the simulation of a typical commercial building.

The same small office model presented in Figure 1 is used for the comparison. Most of the default settings in the prototype building model (U.S. Department of Energy, n.d.) remain the same as in this numerical experiment and are not listed in detail. Settings that are specifically designed for this experiment are:

- The simulation period is 1-day and the simulation time step is 1-minute.
- All perimeter zones are served by ideal load systems.
- Core_ZN is served by a default direct expansion heat pump system developed using the HVAC templates in EnergyPlus.
- All thermostats have the same setting: 22.22 °C (72 °F) cooling setpoint, 20 °C (68 °F) heating setpoint, and 0.56 °C (1 °F) temperature difference between cutout and setpoint. With this thermostat setting in a cooling scenario, the HVAC system shuts down when the temperature drops below 21.67 °C (71 °F) and remains off until the temperature rises above the cooling setpoint. It reflects a typical on/off control.

Tests are performed on a summer day (July 6th) in Atlanta, GA, USA, using TMY3 weather data.

The following three cases with different internal mass modeling settings are tested:

- IntMassArea=0 & C_T=1:
  In this case, no InternalMass object is specified for Core_ZN and the air capacitance is not changed. This is an empty zone case.
- IntMassArea=2xFlrArea & C_T =1:
  In this case, the default values for specifying an InternalMass object in the commercial prototype building model (U.S. Department of Energy, n.d.) are adopted. The same construction material presented in Table 2 is used in the InternalMass object. The size of the internal mass surface area is equal to twice the floor area, which is taken as a “typical” amount of internal mass.
- IntMassArea=0 & C_T=8:
  In this case, the alternative approach for specifying internal mass is employed. The temperature capacity multiplier of Core_ZN is set to 8 to represent a “typical” amount of internal mass as suggested by Lee and Hong (2017).

Figure 4 and Figure 5 present the zone temperature dynamic and HVAC power with and without InternalMass object, respectively. The oscillation of these profiles is typical for HVAC systems with on/off control. As can be seen from the figures, adding a “typical” amount of internal mass through the InternalMass object slightly increases the on/off frequency of the HVAC system. This is mainly due to the increase of internal surfaces that are capable of absorbing heat, resulting in a small increase in zone sensible cooling load (as shown in Table 4).

Figure 6 and Figure 7 depict the zone temperature dynamic and HVAC power with and without temperature capacity multiplier, respectively. Compared to the InternalMass object approach, adding a “typical” amount of internal mass using a temperature capacity multiplier significantly decreases the on/off frequency of the HVAC system. However, the increased damping behavior not only slows down the temperature rise when the system is off, but also slows down the cooling when the system is on. As a result, each cooling period is longer.

Table 4 summarizes the average zone sensible cooling load and HVAC power of each case. The zone sensible cooling load is calculated by replacing the Core_ZN heat pump system with an ideal load system. The way that the InternalMass object specifies the internal mass by increasing the internal area leads to an increase in the zone cooling load (or a reduced heating load in the case of heating), while the impact of changing zone air capacitance on building load is imperceptible. For the approach of changing zone air capacitance, despite the imperceptible change in building load, the overall energy consumption decreases slightly mainly due to the decrease in the on/off frequency.

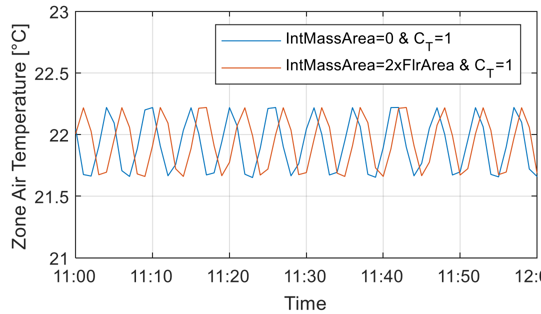

Figure 4: Temperature dynamics with and without InternalMass object.

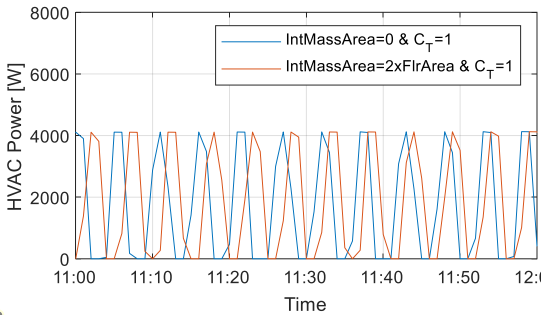

Figure 5: HVAC power with and without InternalMass object.

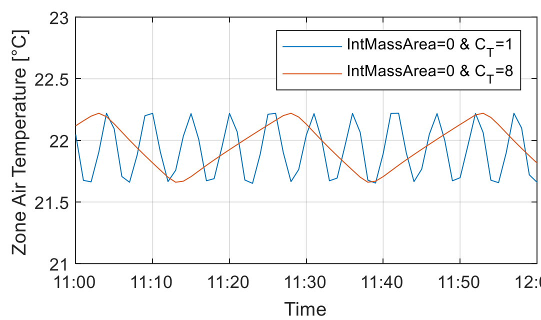

Figure 6: Temperature dynamics with and without temperature capacity multiplier.

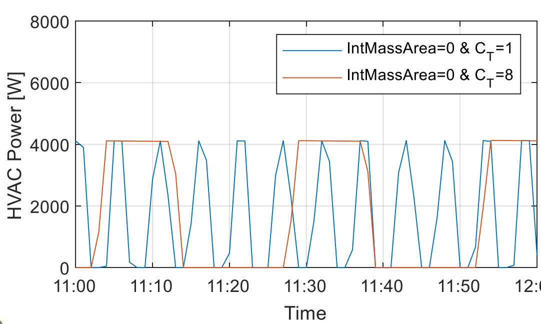

Figure 7: HVAC power with and without temperature capacity multiplier.

Table 4: Average zone sensible cooling load and HVAC power

Case	**Average zone sensible cooling load [W]**	**Average HVAC power [W]**
IntMassArea=0 & C_T=1	2044	1168
IntMassArea=2 xFlrArea & C_T=1	2219	1261
IntMassArea=0 & C_T=8	2044	1134

Zone temperature dynamics in a real building

In this section, we hope to establish an intuition for the readers about the effect of the internal mass on zone dynamics by observing the dynamics of the zone air temperature in real buildings. Our data are HVAC system operational data, which contain measurements for HVAC system control, such as zone air temperature/humidity, supply air temperature/humidity/air flow rate, etc. Some details about the building zone such as building construction materials, surface temperature, floor area, internal load schedule, etc., are not included. Due to the limited nature of the data, we will observe from a macro perspective and try to comprehend the rate of zone temperature variation in typical buildings. For this purpose, we mainly focus on the magnitude of the zone temperature rise in the first 10 minutes when the HVAC system is shut down.

The real building data comes from two sources. One is the summer HVAC operational data (Wen & Li, 2011) from a south facing room at the Iowa Energy Center Energy Resource Station (ERS). This building represents a small office building. The zone is an empty zone with no internal mass. The other data source is summer HVAC operational data (Chen, 2019) from Nesbitt Hall at Drexel University. This building represents a typical medium-sized campus office building consisting of classrooms, conference rooms, offices, and laboratories. The data only comes with labels at the system level, and therefore the correspondence between data points and zones is unknown. It is only known that most of the zones are perimeter zones.

Table 5 summarizes the zone temperature rise, T_{rise}, 10 minutes after HVAC system shutdown. Both real building data and simulation data are presented. In the table, Q_{sen} is the zone sensible cooling load right before system shutdown. For the real building, the sensible load is calculated by comparing the zone inlet and outlet air conditions. Notice again that this is not an apples-to-apples comparison since differences among buildings are not known. The floor area and the sensible cooling load are only provided as a reference and there is no proportional relationship between them and the temperature rise. The simulation data in the table is generated using Perimeter_ZN_1 in the same small office model as shown in Figure 1. All zones are served by ideal loads systems, and they are shut down at 19:00. The data corresponds to a summer day (July 6th) in Atlanta, GA, USA.

Table 5 Zone temperature rise 10 minutes after HVAC system shutdown

Building	Internal mass level	Floor area [m^2]	Q_{sen} [W]	T_{rise} [°C]
ERS	Empty	24.06	2815	1.98
Nesbitt	Typical	9.29 to 112.34	300 to 4684	0.06 to 0.67
Small Office Prototype	IntMassArea =0 & C_T=1	113.45	2381	1.97
Small Office Prototype	IntMassArea =2xFlrArea & C_T=1	113.45	2663	1.89
Small Office Prototype	IntMassArea =0 & C_T=8	113.45	2351	0.37
Small Office Prototype	IntMassArea =2xFlrArea & C_T=8	113.45	2634	0.40

As can be seen from the real building data, the temperature of an empty zone can rise rapidly in a short period of time, while zones with typical internal mass rise relatively slower. From the simulation results, the cases without increased zone air capacitance, i.e., C_T=1, behave more similarly to an empty zone in a real building in the short period after system shutdown, while the cases with increased zone air capacitance closely resemble a zone with typical internal mass. Varying the zone air capacitance to better capture the temperature dynamics over a short period of time is thus necessary. The typical value of 8 suggested by Lee and Hong (2017) is found to be reasonable in this comparison.

Conclusion

In this paper, we demonstrated the impact of two different internal mass modeling approaches in EnergyPlus on the simulation of temperature dynamics and system control studies through the analysis of heat balance equations, parametric analysis, and numerical experiments. We also analyzed a limited amount of real building data to get a glimpse of the internal mass impacts in real life. Overall, the two internal mass modeling approaches have very different emphases. The InternalMass object focuses on the long-term effects of internal mass, while the zone air capacitance approach focuses more on the short-term damping effects. While the two approaches do not bring significant differences in peak load estimation, they do produce different dynamic in terms of temperature simulation, which may lead to different conclusions for studies focusing on temperature dynamics, such as studies on load flexibility, control strategies, zone temperature setpoint reset strategies, space habitability after power outages, thermal autonomy, and other related topics. Therefore, appropriate internal mass modeling is essential for a physics-based simulation study. For studies that involve EnergyPlus physics-based building simulations in which the definition of a so-called "typical" internal mass is desired, we believe that it is a good practice to adopt both the "typical" internal mass surface area as defined in the commercial prototype building models (U.S. Department of Energy, n.d.) and the "typical" temperature capacity multiplier of 8 suggested by Lee and Hong (2017). The authors would like to emphasize that in practical applications it is necessary to use a hybrid approach and to calibrate the parameters of both approaches simultaneously, because the hybrid approach can yield more realistic zone temperature dynamics, especially when the zone is conditioned with heat pump systems with on/off cycling.

Lee and Hong (2017) provides a very reliable inverse method for determining the temperature capacity multiplier using high-fidelity lab data. However, this method is heavily dependent on the completeness and lack of uncertainty of the dataset. Future research is needed to effectively estimate the two internal mass parameters simultaneously using limited and uncertain HVAC operational data. With a clear understanding of the physical principle of the heat balance equation, we may be able to obtain these important parameters by fitting exponential models to the data.

Acknowledgement

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Nomenclature

t = time

T_z = zone air temperature

C_Z = zone air heat capacitance

$\sum_{i=1}^{N_{sl}} \dot{Q}_i$ = sum of the convective internal loads

c_p = air specific heat

h_i = convective heat transfer coefficient of surface i

A_i = surface area of surface i

T_{si} = surface temperature of surface i

$\dot{m}_i$ = mass flow rate from the adjacent zone i

T_{zi} = zone temperature of the adjacent zone i

$\dot{m}_{inf}$ = infiltrated air mass flow rate

T_o = outdoor air temperature

$\dot{m}_{sup}$ = supply air mass flow rate of the HVAC system

T_{sup} = supply air temperature of the HVAC system

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