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A Semi-Empirical Model for Studying the Impact of Thermal Mass and Cost-Return Analysis on Mixed-mode Ventilation in Office Buildings

Haojie Wang[1] and Qingyan Chen[2,1,*]
[1]School of Mechanical Engineering, Purdue University, West Lafayette, IN 47907, USA
[2]School of Environmental Science and Engineering, Tianjin University, Tianjin 300072, China
[*] Phone: (765)496-7562, Email: yanchen@purdue.edu

Abstract:
Mixed-mode ventilation that combines natural ventilation and mechanical ventilation has great potential to save cooling energy when compared to mechanical systems and is more reliable than natural ventilation systems. This paper investigated the impact of window opening area, insulation, and thermal mass on the cooling energy saving of mixed-mode ventilation for three office buildings in different types of U.S. climates using EnergyPlus simulations. The results show that electricity use can be reduced by 6-91% depending on the climate. In addition to climate, thermal mass has a large impact on the performance of mixed-mode ventilation. This investigation developed a semi-empirical model to predict the impact of thermal mass on energy use, and optimized the thermal mass for maximum monetary return based on the model.

Keyword: Mixed-mode ventilation; thermal mass; cost-benefit analysis; EnergyPlus

Nomenclature

A	Area	$\bar{Q}_{out}$	Mean outflow rate
C	Model constant	T	Temperature
C_d	Discharge coefficient	t	Building lifetime in years
C_p	Pressure coefficient	$\bar{U}$	Mean wind velocity
c_p	Specific heat of thermal mass	V_{mass}	Total thermal mass
d	Thickness	z	Vertical location
E_{ME}	Energy consumption by mechanical ventilation	z_0	Vertical location of the neutral plane
E_{saving}	Energy saving by mixed-mode ventilation	ρ	Density
h	Convective heat transfer	τ	Time constant of thermal mass

	coefficient		
h_1	Elevation of the lower edge of the window	Subscript	
h_2	Elevation of the upper edge of the window	i	Indoor air
l	Opening width	m	Thermal mass
P	Pressure	o	Outdoor air
$\bar{Q}$	Mean flow rate	ref	Reference value at 10 m
$\bar{Q}_{in}$	Mean inflow rate		

1. Introduction

In the United States, buildings consume about 40% of total primary energy [1], and the energy consumption of office buildings comprises about 10% of the total building energy usage [2]. Natural ventilation has great potential for reducing the energy consumption in buildings [3, 4]. However, several studies have found that natural ventilation may not provide good thermal comfort during a certain time of year in many locations [5, 6], especially for commercial buildings such as office buildings [7]. Moreover, natural ventilation may not be used when it is raining or too windy. A more reliable ventilation system is needed that can provide the same thermal comfort as a mechanical system and consume less energy. Mixed-mode ventilation that combines the natural and mechanical cooling modes is a potential solution.

The mixed-mode system uses the natural cooling mode when the outdoor climate is suitable. The mechanical mode is used as a backup when outdoor conditions are not favorable. This system can therefore save energy and provide better indoor air quality than a pure mechanical system [8, 9]. The system can also provide better thermal comfort than a pure natural ventilation system [10, 11]. Furthermore, this system is highly integrable and can be coupled with, for example, a night-cooling strategy to further reduce the energy consumption in buildings [12].

Although mixed-mode ventilation has great potential to reduce energy consumption and to improve indoor air quality, design optimization is still needed to ensure the optimal performance of this system. Most of the current research focuses on active optimization, namely, the use of an advanced control algorithm to achieve better performance. Some researchers have developed advanced automatic control strategies for mixed-mode ventilation [13, 14]. They have deployed advanced control algorithms, such as a predictive algorithm with automatic windows and multiple sensors to control the natural ventilation mode and mechanical mode. Such a system, although it has the potential for significant energy saving, is expensive and may easily lead to fouling of the system. On the other hand, some researchers have focused on occupants' control of mixed-mode ventilation [15, 16]. Control based on occupant behavior is more feasible because the majority of buildings require occupants' active interaction with window control when mixed-mode ventilation is used. However, because there are a number of uncertainties in occupant-based control, a deterministic solution is difficult to obtain and therefore to optimize [17, 18].

The other type of design optimization is a passive approach: changing the building construction materials to achieve better performance. To date, few researchers have addressed this approach specifically for mixed-mode ventilation. However, there have been studies of passive building optimization for pure natural ventilation [19 - 21], in which the researchers identified the thermal mass as a very important factor. They found that an increase in thermal mass can reduce the peak temperature by 1-3 K for buildings using free-running natural ventilation with a night-cooling strategy. Because we could also use a night-cooling strategy for the natural ventilation mode in mixed-mode ventilation, thermal mass could have a large impact on the energy performance in our investigation.

This study, therefore, focused on the passive approach to improving energy efficiency for mixed-mode ventilation. This investigation aimed to demonstrate the impact of several important building envelope factors, such as thermal mass, insulation, and window opening area, on mixed-mode ventilation performance. A cost-return analysis was conducted to find the optimal design for thermal mass in order to yield the maximum return for office buildings, taking into account of the capital cost and the return from energy saving during the summer.

2. Research Method

This study investigated buildings with mixed-mode ventilation in five different cities: Miami (Climate Zone 1, very hot and humid), Phoenix (Climate Zone 2, very hot and dry), Las Vegas (Climate Zone 3, hot and dry), San Francisco (Climate Zone 3, marine climate), and Philadelphia (Climate Zone 4, warm and humid) [22] using EnergyPlus simulations. Because mixed-mode ventilation has much larger cooling saving than heating saving in the U.S. [23], this study focused on cooling performance. Therefore, cold climates were not studied, and the time period of the simulation was from May 1 to Sept 30.

This investigation studied typical office buildings of three different sizes. The smallest one had a floor area of 225 m^2, representing typical small office buildings in the U.S [1]. The medium one had a floor area of 600 m^2, which, according to Deru, et al. [24], covers 70% of typical commercial buildings in the U.S. The largest building had a floor area of 1500 m^2 to provide a wider range of data. Buildings larger than 1500 m^2 are often uniquely designed and cannot be represented by one specific model [25]; thus, they are not included in this study.

Figure 1 shows the various building zones as represented by different colors. For the 225 m^2 building, as shown in Figure 1(a), this study used three zones. Each zone could be naturally ventilated because the building depth was small [6]. For the other two buildings, as depicted in

Figure 1(b), five zones were used, and only the four perimeter zones could be naturally ventilated because the core zone did not have direct exposure to outdoor air. Each zone was conditioned by a separate constant air volume (CAV) system to enable individual control [24]. The mechanical system was a packaged rooftop heat pump, and it was automatically sized according to the design day for each climate. Because humidity is a problem in some climates, both humidity and temperature were controlled.

Table 1 lists the detailed information for the building enclosure used in this study. The building envelope constructions were from the Online Building Component Library [26] and based on ASHRAE Standard 90.1 [22]. The baseline buildings had no thermal mass in the building envelope, and different amounts of thermal mass were added to the building in order to study the impact of thermal mass on cooling energy use. For the baseline building which has no concrete in building envelope, the floor slab contained only carpet. Although this is floor structure is not possible in reality, this configuration was used to make the thermal mass comparison more consistent. The insulation for the baseline buildings was based on ASHRAE Standard 90.1 [22] for small or medium office buildings. Additional insulation was added to non-baseline buildings to study its impact. ASHRAE Standard 90.1 [22] requires the glazing-to-wall ratio to be within 0-40%. This study chose a ratio of approximately 20% for each building. The operable window area for natural ventilation was assumed to be half of the total glazing area. The schedules and corresponding values for occupants, lighting, and electrical equipment were based on ASHRAE Standard 90.1 [22] for working and non-working hours [26]. A humidistat was used to avoid condensation when relative humidity was high by overcooling 2 K lower than the cooling setpoint. Natural ventilation would be used when the outdoor temperature was between 15 °C and 22 °C and the indoor temperature was higher than 19 °C during working hours. During non-working hours, natural ventilation would be used when the outdoor temperature was between 10 °C and 22 °C in order to utilize night cooling.

This study considered only single-sided ventilation because in typical office buildings, the interior doors between rooms are usually closed for privacy. Also, even though buildings may have operable windows on each side of the envelope, cross-ventilation is still difficult to realize because of the large depth of buildings or interior partitions. Moreover, single-sided ventilation would provide us with the baseline ventilation rate for the worst-case scenario, which is suitable for design analysis. A modified model that includes the effects of both wind and buoyancy, based on Wang and Chen [27], was used to predict the mean single-sided ventilation rate. The pressure difference between the indoor space and outdoor environment at height z along the opening was calculated based on the stack and wind pressure difference across the opening, using the following equation:

$$\Delta\bar{P}(z) = \frac{1}{2}\rho_o C_p \frac{\bar{U}^2}{z_{ref}^{\ 2/7}}\left(z^{2/7} - z_0^{\ 2/7}\right) - \rho_i g(z - z_0)\frac{T_i - T_o}{T_o} \tag{1}$$

The neutral level, z_0, is an additional unknown which can be calculated from the mass balance equation between the incoming and outgoing ventilation rates through the opening as:

$$\bar{Q} = \bar{Q}_{in} = \bar{Q}_{out} \tag{2}$$

Thus, the mean ventilation rate for single-sided ventilation can be calculated as:

$$\bar{Q} = C_d l \int_{z_0}^{h_2} \sqrt{\frac{2\Delta\bar{P}(z)}{\rho_i}} dz = C_d l \int_{h_1}^{z_0} \sqrt{-\frac{2\Delta\bar{P}(z)}{\rho_o}} dz \tag{3}$$

The above model was implemented in EnergyPlus and used to calculate the ventilation rate for each zone with natural ventilation.

To quantify the impact of thermal mass on mixed-mode ventilation, this study developed a semi-empirical correlation based on the EnergyPlus simulation results. This model is a tool for quickly predicting the impact of thermal mass without performing a large number of simulations. Using the same weather data, the equation is a function of the building design parameters, namely,

$$E_{saving} / E_{ME} = F(Thermal Mass, R-value, Building Size, Window Area...) \tag{4}$$

Based on the lumped capacitance model, the empirical model in dimensionless form for prediction of the impact of thermal mass is

$$E_{saving} / E_{ME} = C_1(\tau / \tau_0 - C_2)\left(1 - \exp\left(-\frac{1}{\tau / \tau_0 - C_2}\right)\right) \tag{5}$$

where $\tau = \rho_m c_p d / h$ is the time constant of thermal mass; τ_0 is set to a unit hour to non-dimensionalize the time constant; and C_1 and C_2 are related to the floor area of the building. Using data interpolation,

$$C_1 = C_3(\exp(-\phi) + C_4) \tag{6}$$

$$C_2 = -C_5\phi + C_6 \tag{7}$$

where $\phi = A / A_0$ and A_0 is set to be 225 m^2, which was the smallest floor area in this study. C_3 to C_6 are the parameters determined by the weather data and insulation level. When the coefficients are known for a certain climate, only one simulation is needed for the pure mechanical system, and Eq. 5 is used to obtain the energy saving for mixed-mode ventilation with various thermal mass configurations.

The model is then used to conduct an economic analysis for mixed-mode ventilation. Although the use of thermal mass can save energy in mixed-mode ventilation, the material and labor costs should also be considered so that excessive thermal mass is not added. Monetary return can be calculated simply as:

$$\text{Return} = \text{Annual energy saved} \times \text{t} - \text{Initial costs} \qquad (8)$$

where t is the building lifetime. For each building lifetime, there exists an optimal amount of thermal mass which would give the maximum monetary return when mixed-mode ventilation is used. For this study, we used concrete as thermal mass, as an example to illustrate this principle. The total amount of concrete is a function of concrete thickness when the area of the building envelope is fixed. To find the optimal concrete thickness, we calculated the first derivative of Eq. 8 with respect to concrete thickness and set the derivative to zero, which yields

$$C_1 Cost_{elec} E_{ME} t \left(1 + \left(\frac{(C_2 - C_1 \frac{\rho_m c_p d / h}{\tau_0})}{(\frac{\rho_m c_p d / h}{\tau_0} - C_2)^2} - 1 \right) \exp\left(-\frac{1}{\frac{\rho_m c_p d / h}{\tau_0} - C_2} \right) \right) = Cost_{concrete} A_{concrete} \frac{\tau_0 h}{\rho_m c_p} \qquad (9)$$

The above equation provides the correlation between the building lifetime *t* and the corresponding optimal concrete thickness *d*.

3. Results

3.1 Impact of Thermal Mass

Figure 2(a) shows the impact of thermal mass on the cooling electricity saving in Philadelphia for three office buildings with different floor areas. The x-axis is the concrete time constant, which is proportional to the concrete thickness. The results from EnergyPlus simulations and the predictions by Eq. 5 were compared, and they are in good agreement, as shown in Figure 2(a). The results demonstrate that, when there was an initial increase in the concrete thickness, the growth rate of energy saving was large. The growth rate then decreased when more thermal mass was added, and finally the energy saving remained almost constant. These results indicate that adding excessive thermal mass would not provide more energy saving; instead, it would only increase the capital cost, which should be avoided. Also, Figure 2(a) shows that adding thermal mass had more impact in a small office with a 225 m^2 floor area than in the two larger buildings because the core zone of the larger buildings could not be naturally ventilated. Thus, concrete added to the floor slab at the core zone could not be used to store cooling potential during the night, which made adding thermal mass less effective. We observed similar results for the Las Vegas and San Francisco climates.

On the other hand, in Miami where outdoor temperature is extremely high during the summer, adding thermal mass might decrease the energy saving for cooling, as shown in Figure 2(b). Typically, in very hot climates, the period that is suitable for night-cooling is very short, usually less than 4 hours per a day based on this study. Therefore, if too much thermal mass was added to the building, resulting in a much longer time constant than the period for night-cooling, the thermal mass would not be cooled down and thus would not provide cooling potential during the daytime. We observed a similar result for Phoenix, which has a hot climate as in Miami. Moreover, both cities had very little energy saving potential for cooling. Therefore, in this study we focus our modeling and cost-return analysis only on Philadelphia, Las Vegas, and San Francisco, where mixed-mode ventilation has great energy saving potential.

Figure 3 summarizes the results of the EnergyPlus simulation and the predictions from Eq. 5 for Philadelphia, Las Vegas, and San Francisco. The comparison shows that the predictions by the model generally had an error of less than 10% for all three climates. Hence, we could use the semi-empirical model to predict the impact of thermal mass without performing a large number of EnergyPlus simulations for different thermal mass configurations, and then use the results to conduct a cost-return analysis.

The previous results showed that adding excessive thermal mass would not yield an improvement in energy saving. To identify the optimal amount of thermal mass needed for mixed-mode ventilation, this study conducted a cost-return analysis. Eq. 8 was used to calculate the total monetary return, taking into account of the cost of concrete and the reduced electricity consumption for cooling. Figure 4 shows the financial benefits for office buildings with lifetimes of 50 years and 100 years, respectively, with mixed-mode ventilation. The optimal concrete thickness, which gave the maximum return, was about 3 cm for a small office building with a floor area of 225 m^2, and less than 1.5 cm for a building with a floor area of 1500 m^2. Adding excessive thermal mass would decrease the return or even result in a negative return because of the high capital cost.

In the design of a building with mixed-mode ventilation, the amount of concrete needed to achieve the maximum return would be a function of the expected building lifetime. To find the relationship between building lifetime and optimal concrete thickness, Eq. 9, which is the first derivative of Eq. 8 with respect to time, was used; the results are plotted in Figure 5 for three office buildings with different floor areas. Figure 5 shows that more concrete is needed to achieve the maximum return over a longer period of time when mixed-mode ventilation is used. Also, a small building requires thicker concrete than a large building. This study used concrete as the thermal mass material, but concrete cannot be used to retrofit existing buildings. However, there are other heat storage materials such as phase change materials that can be injected into a building envelope [28, 29]. A cost-return analysis for retrofitting with this type of material can be conducted by applying Eqs. 5, 8 and 9 in the same manner as above.

3.2 Impact of Climate

Figure 6 shows the electricity saving for cooling by mixed mode ventilation as compared to a pure mechanical system for different climates, calculated by EnergyPlus. The figure compares the baseline buildings (without thermal mass) and buildings with 200 mm thick concrete (the largest amount of thermal mass used in this study) in the exterior wall and floor slab. The results show that in San Francisco, where the temperature is mild all year long, the climate is in favor of using natural ventilation, which could save more than 60% of the total energy for cooling even without concrete. On the other hand, in Las Vegas and Philadelphia, where the daytime temperature during the summer is high and the night-time temperature is low, the increase in the thermal mass together with night cooling could improve the energy saving significantly. However, for extremely hot climates such as in Phoenix and Miami, adding thermal mass would not be effective because of consistently high temperatures above the comfort level. Figure 6 also shows that adding thermal mass can lead to greater energy savings for small buildings than for larger buildings.

3.3 Impact of Insulation

This study also investigated the impact of envelope insulation on the energy saving of mixed-mode ventilation. The baseline insulation was based on ASHRAE Standard 90.1 [22]. Additional insulation was added to the exterior wall and roof of the baseline buildings. Figure 7 shows the impact of the insulation on the electricity saving for cooling in San Francisco, Las Vegas, and Philadelphia as calculated by EnergyPlus. The “Relative R-value” in this figure is the ratio of the R-value of a building to its corresponding baseline building. The results show that the addition of more insulation would generally increase the energy saving for all three climates. In a mild marine climate such as San Francisco, the impact of insulation is much smaller than in warmer climates such as Las Vegas or Philadelphia. Since many researchers have extensively studied the optimization of insulation [25, 30], this study did not conduct a further cost-return analysis for insulation.

3.4 Impact of Opening Area

This study also investigated the impact of window opening area on the electricity saving for cooling by simulating three opening states: (a) fully open; (b) half open; and (c) one-quarter open. The impact of the window opening area on energy saving was relatively small for both the baseline building and the buliding with 200 mm of concrete. The EnergyPlus results in Figure 8 indicate that even with only 25% of the total operable window area open, the ventilation rate was sufficient. A further increase in the window opening area would increase the heat transfer coefficient moderately but would not lead to higher heat transfer from building structure to air. Artmann et al. [21] also found that the ventilation rate did not have a very noticeable impact on the daytime temperature when the average night air exchange rate was larger than 6 ACH for natural ventilation.

4. Conclusions

This study developed a semi-empirical model to predict the impact of thermal mass on electricity saving for cooling and used the model to conduct a cost-return analysis. The results calculated by the empirical model are similar to those calculated by the EnergyPlus program.

This investigation also studied the impact of thermal mass, climate, insulation, and window opening area on the energy saving of mixed-mode ventilation in typical office buildings. In a variety of climates, mixed-mode ventilation consumed 0-77% less electricity than a pure mechanical system for cooling when no thermal mass was added, and 6-91% less when 200 mm of concrete was added to the exterior wall and floor. The results showed that the thermal mass and insulation have a large impact on energy saving.

Our analysis showed that there was an optimal amount of thermal mass that yielded the maximum return, taking into account of the cost of thermal mass and the cost saving from the reduction in energy consumption. The optimal thermal mass can be used as a guideline for designing new buildings or retrofitting existing office buildings for mixed-model ventilation.

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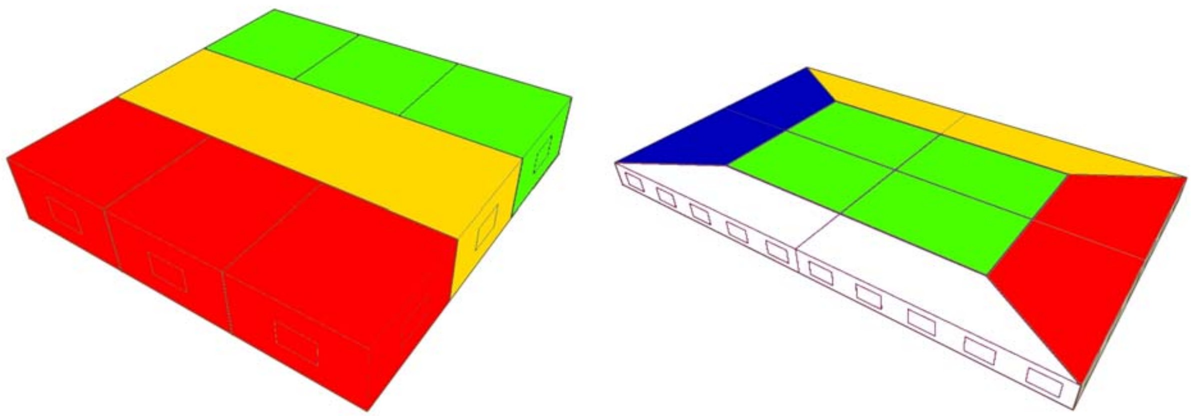
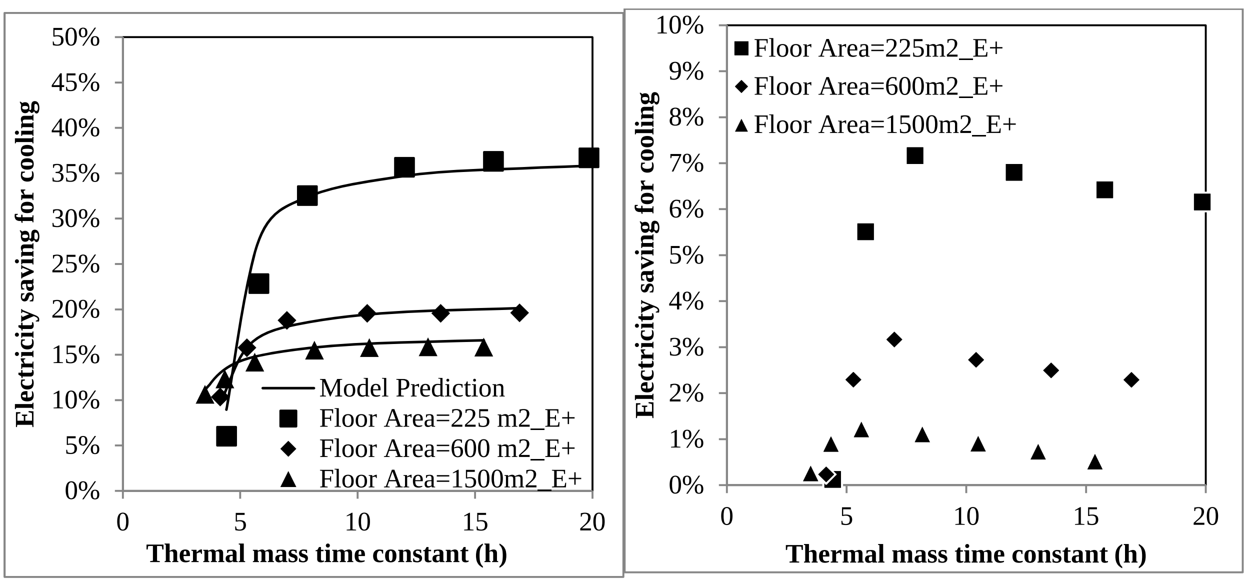
Table 1 Building information used for the simulations

Floor area (m^2)	225	600	1500
Space type [26]	Small office	Small office	Medium office
Period of simulation	May 1 to September 30		
Weather data	TMY3 for Philadelphia, PA; Phoenix, AZ; Miami FL; Las Vegas, NM; and San Francisco, CA		
Exterior wall construction (from outside to inside)	25 mm stucco/ Insulation (baseline from [26])/ Thermal mass (baseline: no thermal mass) / 12.7 mm gypsum		10 mm wood siding/ Insulation (baseline from [26]) Thermal mass (baseline: no thermal mass) / 12.7 mm gypsum
Interior wall	19 mm gypsum board/ R-0.15 airspace resistance/ 19 mm gypsum board		
Roof (from outside to inside)	0.9 mm roof membrane/ Insulation (baseline from [26]) / Metal decking		
Floor (from outside to inside)	Thermal mass (baseline: no thermal mass) Carpet: R=0.216 $K \cdot m^2/W$		
Glazing	U-value from [26]; Solar Heat Gain Coefficient = 0.39		
Electric equipment/ Lighting/ People schedule	Online Building Component Library [26] for small office		Online Building Component Library [26] for medium office
Working hours	8:00-17:00		
Window area (m^2)	18	67	240
Cooling setpoint temperature	Working hours: 24 °C Non-working hours: 29°C		
Dehumidification setpoint	Working hours: 70% Non-working hours: 90%		
Natural ventilation activation criteria	Working hours: 15 °C < T_{out} < 22 °C and T_{in} > 19 °C Non-working hours: 10 °C < T_{out} < 22 °C		



(a) (b)

Figure 1 Building geometries and zones used in EnergyPlus (a) with a floor area of 225 m^2 and (b) with a floor area of 600 m^2 or 1500 m^2.



(a) (b)

Figure 2 Impact of thermal mass on electricity saving for cooling for (a) Philadelphia and (b) Miami

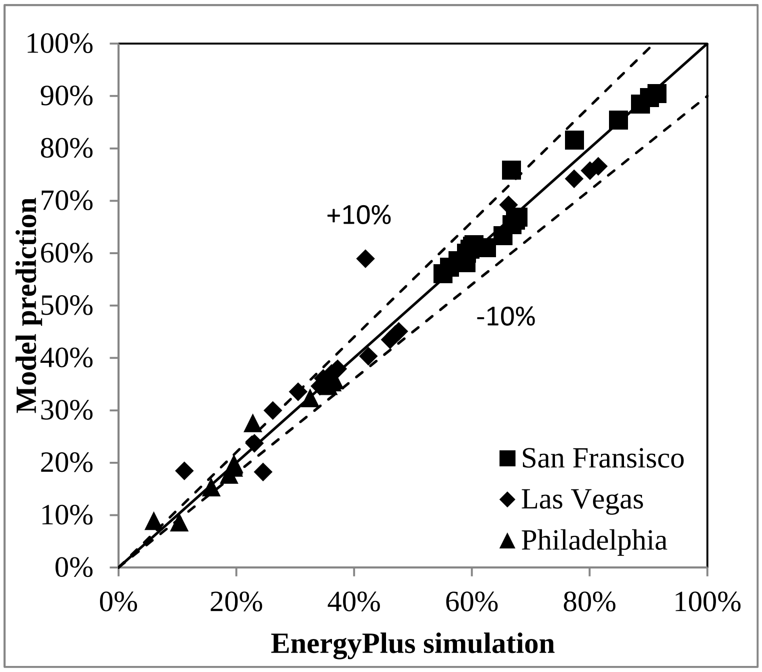


Figure 3 Model predictions of energy saving with natural ventilation vs. EnergyPlus simulations for San Francisco, Las Vegas, and Philadelphia

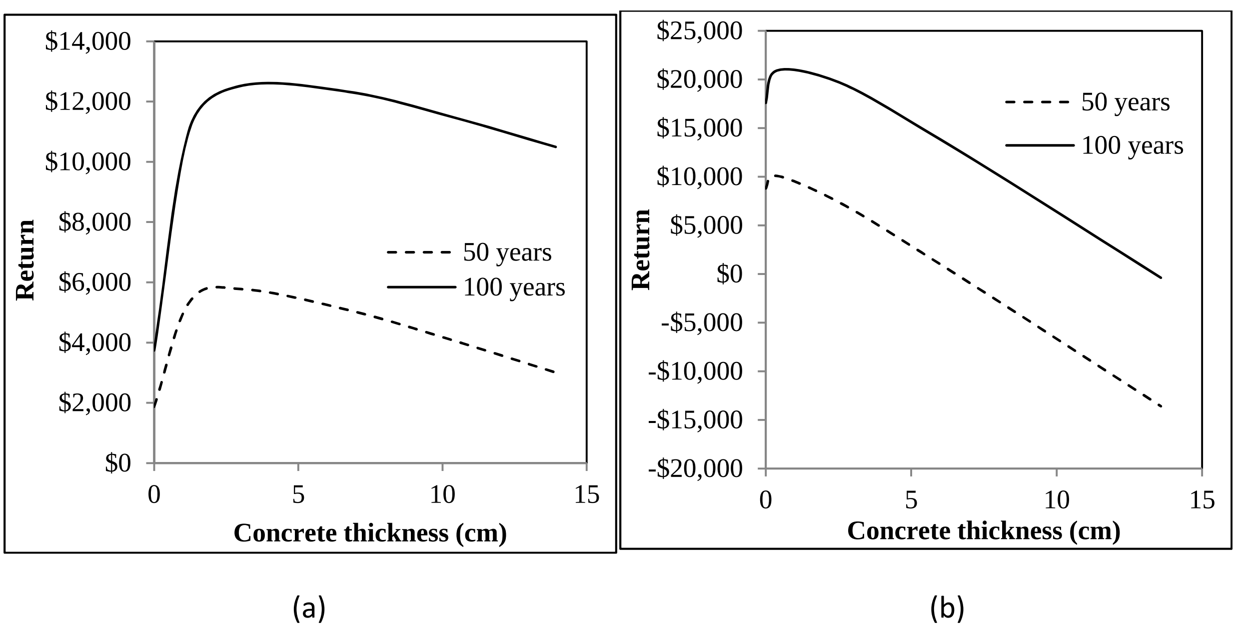


Figure 4 Monetary return over different building lifetimes in Philadelphia for (a) a small office with a floor area of 225 m^2 and (b) a medium office with a floor area of 1500 m^2

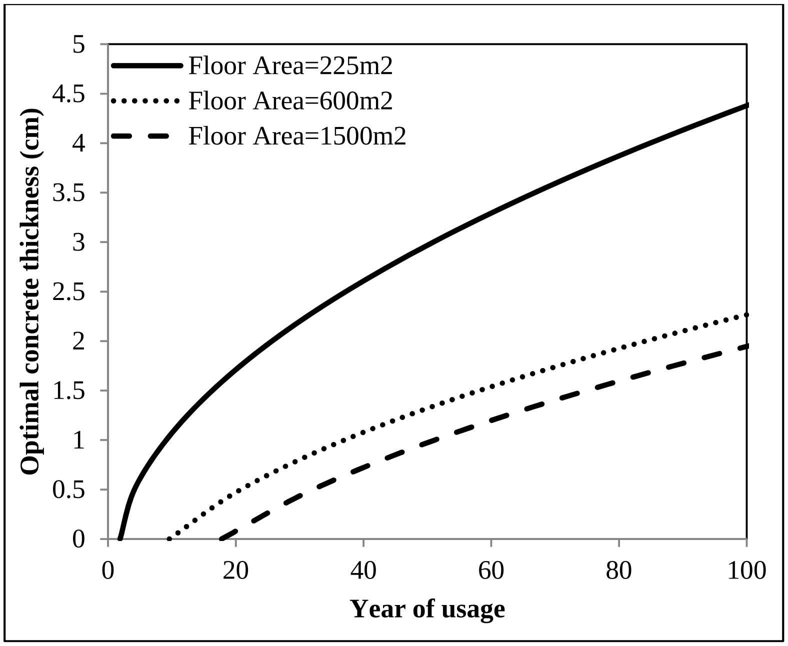


Figure 5 Optimal concrete thicknesses with respect to building lifetime for Philadelphia

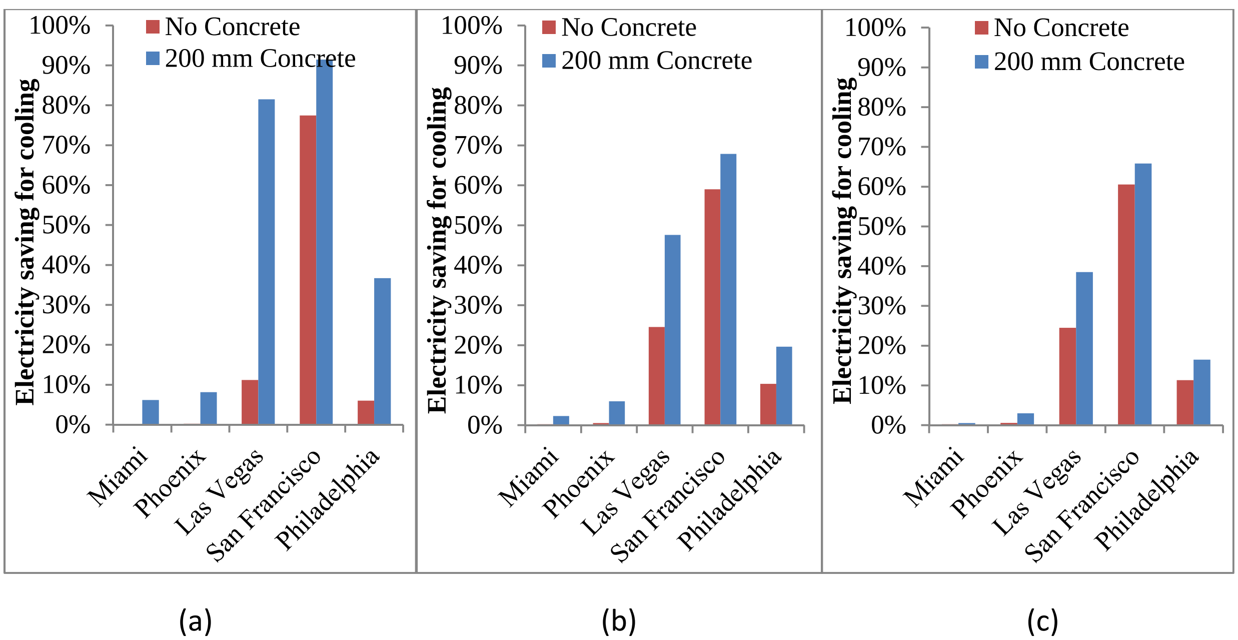
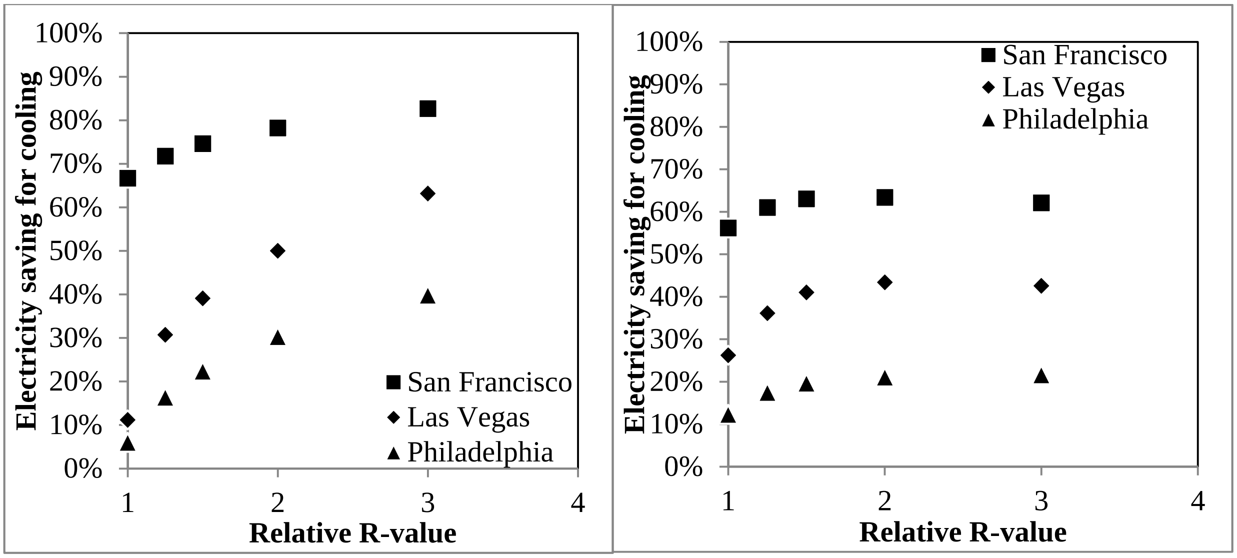
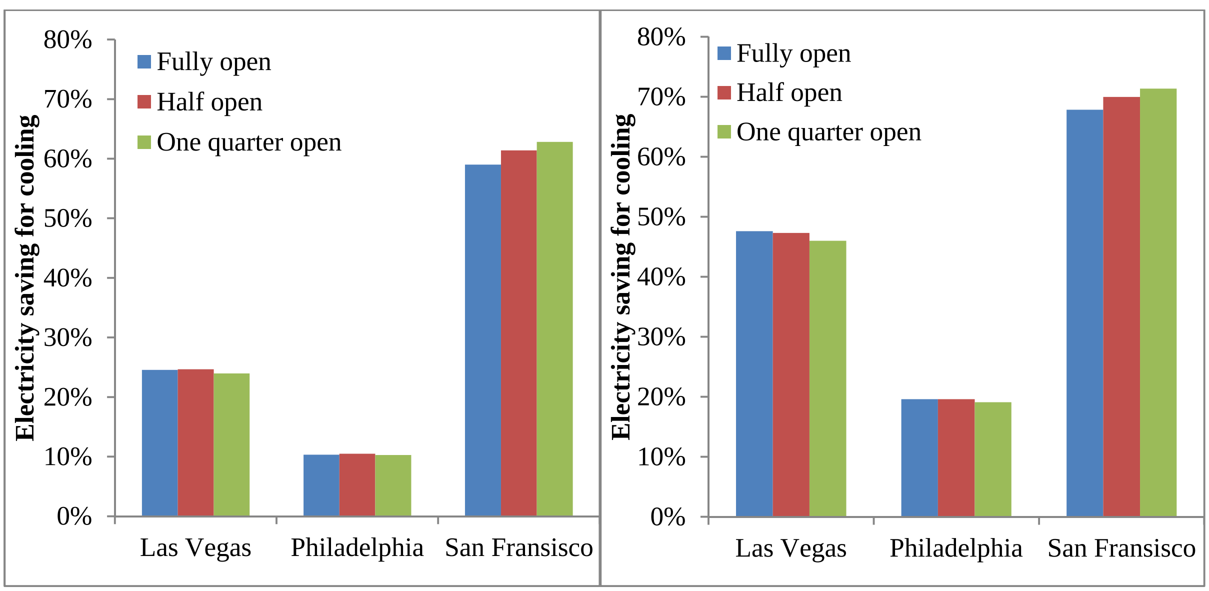


Figure 6 Electricity saving for cooling in different climates for offices with floor areas of (a) 225 m^2, (b) 600 m^2, and (c) 1500 m^2



(a) (b)

Figure 7 Impact of insulation on electricity saving for cooling (a) a small office with a floor area of 225 m^2 and (b) a medium office with a floor area of 1500 m^2



(a) (b)

Figure 8 Impact of window opening area on electricity saving for cooling in a building with a floor area of 600 m^2: (a) baseline building and (b) building with 200 mm of concrete