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Performance evaluation of damper control settings for operation of multiple-zone variable air volume reheat system in different building applications and climate types

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Performance evaluation of damper control settings for operation of multiple-zone variable air volume reheat system in different building applications and climate types

Abstract

Choosing the right control strategies is an important task for effective operation of variable air volume reheat (VAVR) system in commercial buildings. In this design, dampers' position inside air terminal units (ATUs) are modulated to adjust the amount of air supply volume based on thermal zones' cooling or heating demand. A minimum air flow fraction (MAFF) is set for damper settings of ATUs to avoid under-ventilation problem in thermal zones. This study investigated the impact of MAFF value on various performance aspects of multiple-zone VAVR design in different building applications and climate types. A five-storey commercial building for three applications of school, office and retail in four climate types of tropical monsoon, hot desert, Mediterranean and humid continental have been simulated in EnergyPlus building simulation software. The results of simulations have shown that lowering MAFF value in ATUs would reduce the required reheat coil energy to maintain precise air supply temperature at part load cooling scenarios. Nonetheless, this reduction could have some implications on thermal comfort and indoor air quality level of thermal zones in a multiple-zone arrangement. It was concluded that in general it is an energy efficient control strategy to keep MAFF value to as low as 0.1 for high ventilation rate spaces like classrooms in school buildings (except for hot desert climate). On the other hand, it is advisable to not reduce MAFF value below 0.3 for low ventilation rate spaces like office areas to avoid any air quality issues in thermal zones.

Keywords – Damper Control Settings, Variable Air Volume Reheat, Air Terminal Unit, Minimum Air Flow Fraction, Building Simulation, EnergyPlus

1. Nomenclature

AHU	Air Handling Unit
ATU	Air Terminal Unit
CAV	Constant Air Volume
CO_2	Carbon Dioxide
DCV	Demand Control Ventilation
HVAC	Heating, Ventilation and Air Conditioning
IAQ	Indoor Air Quality
MAFF	Minimum Air Flow Fraction
OAFF	Outdoor Air Flow Fraction
SHGC	Solar Heat Gain Coefficient
VAV	Variable Air Volume
VAVR	Variable Air Volume Reheat
ε	Emissivity
σ	Stefan-Boltzmann constant
ρ	Density of Air
c	Heat Capacity
A_{ext}	Exterior Surface Area
M	Mass Concentration
M_{out}	Outdoor Mass Concentration
M_{sup}	Supply Mass Concentration
Q_{exf}	Exfiltration Flow Rate

Q_{exh}	Exhaust Flow Rate
Q_{inf}	Infiltration Flow Rate
Q_{sup}	Supply Flow Rate
R	Thermal resistance
S_T	Source of Heat
S_M	Source of pollutants
T	Temperature
T_{ext}	Exterior Surface Temperature
T_{sky}	Average Temperature of Sky
T_{sup}	Supply Air Temperature
T_{out}	Outdoor Air Temperature
U	Thermal Transmittance
V	Volume

2. Introduction

There are many considerations to be taken into account in order to choose the right control strategies for operation of a HVAC system in buildings. Any efficient HVAC design requires an optimized and robust control system to operate effectively under different indoor/outdoor scenarios (Liu et al. 2014; Nassif, 2013; Saber et al. 2016). The central all air design is the most common type of HVAC system in commercial high-rise buildings. In this design, several chillers and boilers provide chilled and hot water for air handling units (AHUs) and air terminal units (ATUs) located at different floors of building. Each AHU typically serves several thermal zones and provides a conditioned mix of outdoor and return air to terminal units of zones. AHUs and ATUs operate based on constant air volume (CAV) or variable air volume (VAV) strategies. In CAV design, the supply air volume remains constant while supply air temperature is modulated in response to the changing load of space. On the other hand, supply air temperature remains constant in VAV design while air volume is modulated in air terminal units. CAV has lower investment cost and simpler **control system, while VAV has** higher initial cost and requires more sophisticated control strategies to bring in enough outdoor air at part load scenarios. In addition, VAV provides better dehumidification performance at part load operation and it is more suitable for spaces where load characteristics are not well defined or future expansion is predicted (Rengarajan and Colacino, 2004).

ATUs are employed with a reheat coil in multiple-zone design scenarios to concurrently satisfy different cooling/heating loads of zones. In cooling mode, reheat coil provides sensible heating to supply air to maintain precise control of indoor condition without compromising air quality. In actual building operation, each zone has different cooling load and reducing the amount of outdoor air coming into the space could raise air quality concern in some thermal zones connected to the same air loop system. In heating mode, reheat coil provides a **complementary** heating to pre-heated air stream and its capacity could be modulated through valve control to satisfy changing heating demand of zones. The schematic diagram of a multiple-zone VAV design with reheat coils is shown in Fig. 1. Ventilation controller modulates dampers' settings on return air, exhaust air and outdoor air streams to bring necessary amount of outdoor air into thermal zones. In addition, VAV controller modulates damper and valve settings inside air terminal units based on thermostat feedback and air flow sensors in ducts.

Fig. 1 here

The control settings of ventilation and VAV controllers could have considerable impacts on the performance of VAVR design in terms of thermal comfort, air quality and energy consumption. Various studies in the literature attempted to explore the most optimal control strategies for operation of VAVR system in buildings (Murphy 2011; Warden 2004; Xu et al. 2009; Yang et al. 2011). Pan et al. (2003) investigated two high rise office buildings in Shanghai and found that the amount of outdoor air flow rate varies significantly from zone to zone especially in part load operations. They concluded that fixed outdoor air flow fraction (OAFF) of 0.1 to 0.2 is unable to provide necessary ventilation to all zones. In a similar study, Krarti et al. (2000) conducted an experimental evaluation of different air flow measurement techniques and control strategies in order to maintain the minimum level of outdoor air in VAV design. They found strategies using direct measurement of outdoor flow rate using Pitot tube and anemometer as the best control scheme. CO_2 based demand control ventilation (DCV) was found to be an effective strategy for spaces where there are high variations in occupancy level and non-occupant pollutant sources are negligible (Emmerich and Persily, 1997). Xu and Wang (2007) proposed an adaptive DCV with dynamic ventilation equation and critical zone set point temperature reset which can provide better thermal comfort and air quality with energy saving of 7.8 to 9 % for summer condition of Hong Kong. In another study, Nassif (2012) proposed a robust DCV based on CO_2 concentration of supply air for multiple-zone VAV system which has estimated energy savings of up to 25% under different USA climates.

Cho and Liu (2009) evaluated several control strategies of air terminal units and proposed an improved control algorithm which could reduce the energy saving of HVAC system by 33%. Control settings of the damper inside ATUs could play an important role in operation of VAVR system at part load. The minimum amount of supply air volume at part load could be controlled with this damper setting as constant minimum air flow fraction (MAFF) or fixed minimum air flow rate. Liu and Brambley (2011) suggested employing building occupancy sensors to determine minimum air flow set point for each zone or terminal box. In another study, Lee et al. (2012) investigated three MAFF values of 10%, 20% and 30% with

EnergyPlus and found that this value has significant impact on annual energy consumption of boiler. The current study aimed to investigate the impact of damper control settings in performance of multiple-zone VAVR system for different building applications and climate types. **In the common control settings of VAVR, a fixed MAFF is set in air terminal units to bring in enough outdoor air in part load scenarios.** Different values of MAFF have been applied in control settings of the dampers **inside ATUs, and its impacts** on air quality, thermal comfort and reheat coil energy have been explored through building performance simulation.

3. Research Methodology

Each thermal zone in the building represents a control volume in which temperature, humidity, carbon dioxide and other pollutants could be assumed to be uniform. The general heat and mass flows through boundaries inward and outward thermal zone as a control volume are illustrated in Fig. 2. Heat transfer and mass transfer could happen through walls, windows, gaps, air supply diffusers and return grills. There could be radiative, convective/conductive heat gain and heat loss as well as infiltration and exfiltration through doors or windows gaps. Occupants, lighting and equipment inside thermal zone would act as the sources of heat and pollutants which also need to be taken into account.

Fig. 2 here

Heat and mass balance equations for each thermal zone representing a control volume can be written as Eq. 1 and Eq. 2. M denotes mass concentration of any chemical components in air including water vapour (H_2O), carbon dioxide (CO_2), and other indoor air pollutants.

EnergyPlus building simulation software has been employed in this study to model zone heat and mass balance processes in buildings. This open-source software formulates energy and mass balances for thermal zones based on integration of zone and air systems and solves the resulting ordinary differential equations using a predictor-corrector approach (ENERGYPLUS, 2016a).

$$\rho c V \frac{dT}{dt} = \rho c\left(Q_{sup}T_{sup} - Q_{exh}T\right) + \rho c\left(Q_{inf}T_{out} - Q_{exf}T\right) + UA_f\left(T_{out} - T\right) + A_{ext}\varepsilon\sigma\left(T_{sky}^4 - T_{ext}^4\right) + S_T \quad \text{Eq. 1}$$

$$\frac{dM}{dt} = \frac{1}{V}\left(Q_{sup}M_{sup} - Q_{exh}M\right) + \frac{1}{V}\left(Q_{inf}M_{out} - Q_{exf}M\right) + S_M \quad \text{Eq. 2}$$

The geometry of a five-storey commercial building has been modelled in 3D modelling program of SketchUp. The 3D geometry and floor plan of the simulated building are shown in Fig. 3. Each storey has the floor area of 625 m^2 (25 m × 25 m) which is divided into five thermal zones (East, West, North, South, Centre) of the same floor area (125 m^2). All the perimeter zones have the same window and flat overhang dimensions. All the five zones in each floor are connected to one air loop system. Air is supplied to different zones through ATUs which include dampers and reheat coils. As explained in the introduction section, VAV controller modulates damper and reheat coil control settings based on the feedback from thermostat and air flow sensors. A minimum air flow fraction (MAFF) could be set for damper position in ATUs to assure a minimum level of zone ventilation at part load cooling scenarios. In heating mode, damper position remains at MAFF point while reheat valve **gradually opens until supply air** temperature gets to a maximum set point. A maximum air flow fraction in heating mode is also set in dual maximum control logic of ATU to provide higher level of heating capacity by increasing air flow rate in heating mode (Taylor et al. 2012).

Fig. 3 here

The impact of MAFF value on performance of multiple-zone VAVR system has been investigated through building simulation. Three MAFF values of 0.1, 0.3 and 0.5 have been set in control settings of 25 zones' ATUs in the simulated building. The impact of this parameter was explored on several performance metrics related to energy consumption, thermal comfort and air quality. The variation of MAFF value would change the air supply volume at some part load scenarios which could affect the design load of reheat coil or heating energy of building. It also could affect comfort level of occupants and the amount of outdoor air flow rate in some scenarios. Fanger's PMV/PPD model has been used as the comfort metrics in this research. The number of hours in the year when PMV falls out of acceptable range ($-1<PMV<1$, $PPD< 25\%$) was calculated for each simulation scenario (ISO 7730, 2005). In addition, zone CO_2 level has been determined through zone air contaminant balance model in EnergyPlus as an indicator of air quality in thermal zones (ENERGYPLUS, 2016b). The threshold of 1000 ppm has been assumed in this study and the number of hours in the year when CO_2 concentration has exceeded this limit was calculated. Outdoor air flow fraction (OAFF) of the air loop system in each floor was also calculated for the range of simulated MAFF values.

The building simulations have been conducted for different applications and climate types. Three building applications of office building, retail establishment and educational facilities (classroom) have been considered in this study. The specific load characteristics and ventilation requirements of these buildings are listed in Table 1. These numbers were adopted from USA **Department of Energy** commercial prototype building models (DOE, 2016) which represent typical buildings designs in the United States based on ASHRAE standard

90.1 (2013). Occupant density in these buildings has the order of educational > retail > office and the required ventilation rate needs to be modified for each building, accordingly. There are two sets of ventilation rate specified for each building. One is used for sizing of equipment **including fan, coil, etc., and the outdoor** control ventilation is used to specify necessary outdoor air in each application. The impact of MAFF has also been investigated for buildings in different climate types. The simulations have been conducted for four climate types of tropical monsoon (Miami), hot desert (Phoenix), Mediterranean (San Francisco) and humid continental (Chicago). The specific construction characteristics of buildings for each of these climate types are listed in Table 2. These values were also adopted from USA **Department of Energy** commercial prototype building models (DOE, 2016). Colder climate requires higher thermal resistance (R) or lower thermal transmittance (U) in roof insulation, exterior wall insulation and window glazing materials. Solar heat gain coefficient (SHGC) of the selected window for humid continental climate of Chicago is higher than other climates to bring more solar heat into the space for this relatively cold climate. It is noteworthy that in all of the conducted simulations, cooling/heating set point temperatures were set to 24/21 ˚C from 6 AM to 9 PM and 29.4/15.6 ˚C for the rest of the hours in weekdays. Infiltration rate per exterior surface of 0.57 L/s.m^2 was assumed in these building energy simulations and the infiltration level was reduced to a quarter when HVAC system was operating.

Table 1 here

Table 2 here

4. Results

The impact of MAFF value in ATUs was investigated on several performance metrics of the building in different applications and climates. These metrics cover various aspects of building performance including reheat coil energy, thermal comfort and indoor air quality. The simulations have been conducted for three MAFF values of 0.1, 0.3 and 0.5 in three building applications (school, office, retail) and four climate types (tropical monsoon, hot desert, Mediterranean, humid continental). The results of the simulations for school, office and retail buildings are compared to each other in Fig. 4, Fig. 5 and Fig. 6, respectively. The error bars indicate the standard deviation of the calculated values for 25 simulated thermal zones. In general, there is a reduction in reheat coil load of zones when the minimum air flow fraction (MAFF) decreases from 0.5 to 0.3 and 0.1. The level of reduction for the climates where there is no dominant heating demand (Miami, Phoenix and San Francisco) could be up to 40%. However, the reduction level is less than 6% for the continental climate of Chicago. The reheat coil design load for the Chicago climate is three times more than other climates because of higher heating degree days in this climate.

The comfort analysis of the simulations showed that the number of hours when PMV value was not in the acceptable range increases for lower values of MAFF. This increase ranges between 10 to 21% for the tropical climate **of Miami, while for the dry** climate of Phoenix, the level of increase could be up to 106%. On the other hand, the number of uncomfortable hours with reduced MAFF on annual basis seems to be decreasing or remaining unchanged for the temperate climate of San Francisco and continental climate of Chicago. The number of hours when PMV was not acceptable for the tropical monsoon climate of Miami was found to be in the range of **1000 hours, while in other** climate this value was in the range of 500 hours. The specific cooling load profile in the tropics which constitutes a significant portion of latent load could be the reason behind this higher level of uncomfortable hours.

The indoor air quality level of thermal zones was found to be more dependent on application type of buildings. The number of hours when CO_2 exceeds the limit is considerably higher for school buildings compared to office and retail application because of denser occupancy level. However, the level of increase in number of hours for reduced MAFF values remain almost unchanged **for school buildings, while there could** be up to 573% and 58% increase, respectively for office and retail buildings. On the basis of climate types, air quality level in the simulated building has been more affected with reduction of MAFF value in the continental climate of Chicago.

Fig. 4 here

Fig. 5 here

Fig. 6 here

Reducing MAFF value would have some impacts on operational condition of ventilation controller to bring in necessary amount of outdoor air at part load scenarios. Outdoor air flow fraction (OAFF) of air loop systems in the simulated building has been determined throughout the year. The results of the simulations for different building applications and climate types are compared to each other in Fig. 7. The error bars indicate the standard deviation of the calculated values for 5 air loop systems in the simulated building. Outdoor air flow fraction (OAFF) in air handling units of the building was close to 0.4, 0.2 and 0.3 respectively for school, office and retail applications. School and retail buildings have higher OAFF values compared to office building because of denser occupancy. In general, OAFF increases for lower values of MAFF to maintain the same level of ventilation rate or indoor air quality in the space. The level of increase in OAFF is insignificant **for school buildings, while it could** be up to 142% and 47% respectively for office and retail applications.

Fig. 7 here

The OAFF value of the air loop system in building varies depending on the time of the day and the month of the year. The flood plots of OAFF over simulation time for school, office and retail applications in the tropical monsoon climate of Miami are shown in Fig. 8. It can be seen that there is a slight increase in OAFF of AHU systems in buildings during heating season (November to March). The higher OAFF value in heating mode of system could be justified considering the fact that heating demand of thermal zones could be satisfied at minimum supply air flow rate while modulating hot water flow rate in reheat coil. This could require higher OAFF value to bring necessary amount of outdoor air into the thermal zones. As illustrated in these flood plots, OAFF has only nonzero values during occupancy period when HVAC system is operating which mainly includes weekdays from 6 AM to 9 PM.

Fig. 8 here

5. Discussions

Control settings of dampers inside ATUs in multiple-zone VAVR design could have considerable impacts on energy consumption and well-being of occupants inside buildings. The damper position is modulated at part load cooling scenarios to reduce air supply volume according to the cooling demand of space. However, due to the zone ventilation concern, a minimum air flow fraction (MAFF) of design flow rate is set for damper control setting. The MAFF value would affect required reheat energy in both cooling and heating mode. In addition, the ventilation controller needs to adjust outdoor air flow fraction (OAFF) of air loops based on this MAFF value. The functions of VAV controller and ventilation controller in multiple-zone VAVR system are interconnected and reducing the MAFF value could have implications on thermal comfort and air quality of thermal zones.

The results of this investigation revealed that there is a reduction in reheat coil design load for reduced MAFF values. Lower MAFF values would result in decreased air supply volume at part load scenarios which requires less reheat energy to warm up the supply air. The level of reduction in reheat coil load for Miami, Phoenix and San Francisco climates ranges between 14 to 23% and 5 to 20%, respectively when MAFF value decreases from 0.5 to 0.3 and from 0.3 to 0.1. The impact of this parameter on reheat coil load is less pronounced for continental climate of Chicago because the reheat load in this climate is mainly determined by heating demand of zones. The reduction level in this climate is within 3 to 6% and 0.5 to 1%, respectively when MAFF value drops from 0.5 to 0.3 and from 0.3 to 0.1. In a relevant study, Lee et al. (2012) investigated the effect of minimum air flow setting on building energy consumption under Korean climate condition. They studied three MAFF values of 0.1, 0.2 and 0.3 and found that this value has significant impact on reheat energy and consequently on annual energy consumption of boiler. Hoyt et al. (2009) also investigated the impact of lowering the minimum supply air volume for San Francisco climate. They concluded that lowering MAFF value from 0.3 to 0.2 and 0.1 would reduce the annual energy usage by 17% and 27%, respectively.

Thermal comfort analysis of the simulated building showed that in relatively warm climates of Miami and Phoenix, the number of hours when PMV was not in acceptable range increases by lowering MAFF value. However, no similar trend was observed for Mediterranean climate of San Francisco and continental climate of Chicago. Higher cooling load in tropical monsoon climate of Miami and hot desert climate of Phoenix could be the reason behind these differences. In terms of indoor air quality, office spaces were found to be the most vulnerable types of commercial applications for lowering MAFF value. The number of CO_2 exceeded hours on annual basis increases by 203% and 435% respectively for office buildings in San Francisco and Chicago climates when MAFF value decreases from 0.3 to 0.1. It could be said that lowering MAFF value is more likely to cause IAQ issues for spaces with low ventilation rate like in office buildings. The analysis of outdoor air flow fraction (OAFF) in different air loops of the simulated building revealed that OAFF varies significantly depending on application types. Ventilation controller would increase OAFF value in different scenarios to bring enough outdoor air into thermal zones for reduced MAFF values of ATUs. The level of increase in OAFF value is more pronounced in office spaces which ranges between 28 to 55% and 28 to 66% when MAFF value decreases from 0.5 to 0.3 and 0.3 to 0.1, respectively.

It was shown in this investigation that in general it is a good design practice to keep the MAFF value to as low as 0.1 to reduce reheat coil load in part load scenarios. Nevertheless, the results of simulations have shown that reducing MAFF value below 0.3 in some building applications and climate types could cause comfort and IAQ issues for some thermal zones in multiple-zone VAVR design. The number of uncomfortable hours in thermal zones would significantly increase for school buildings in hot desert climate and retail buildings in both Mediterranean and hot desert climates if MAFF value reduces to less than 0.3. In addition, the number of CO_2 exceeded hours is likely to increase considerably for office buildings in the all four simulated climates and retail buildings in continental climate if MAFF setting drops to less than 0.3. It is noteworthy that ventilation controller of VAVR design needs to modulate dampers' position near outdoor intake and adjust OAFF value of air loop system to assure necessary amount of outdoor air in all thermal zones for the range of MAFF values. **The CO_2-based control of air flow fraction with deployed carbon dioxide sensors in air streams or indoor space is an alternative strategy for operation of ATUs which could suit better specific building applications and climate types.**

6. Conclusion

The impact of damper control settings in multiple-zone variable air volume reheat (VAVR) design has been investigated through building performance simulations. Three values of 0.5, 0.3 and 0.1 have been considered for minimum air flow fraction (MAFF) in air terminal units (ATUs) of a five-storey building with 25 thermal zones. The simulations have been conducted for three building applications (school, office and retail) and four climate types (tropical monsoon, hot desert, Mediterranean and humid continental). The outcomes of simulations have shown that reheat coil design load would drop by lowering MAFF value in ATUs of thermal zones. However, this reduction in supply air flow rate at part load scenarios could have some implications regarding thermal comfort and IAQ level in some thermal zones. In general, it is advisable to keep MAFF value to as low as 0.1 for relatively high ventilation rate spaces like school buildings except for school spaces in hot desert climate of phoenix. For relatively low ventilation rate spaces like office buildings, it is the best to not reduce MAFF value below 0.3 since that could considerably deteriorate IAQ level in some thermal zones. In all of the simulated scenarios, ventilation controller of VAVR system adjusted outdoor air flor fraction (OAFF) of air loops based on ventilation demand of zones. The proper and effective function of the ventilation controller is a necessity for providing adequate amount of outdoor air into space for the range of MAFF values. It is recommended for future works to further investigate the impact of damper control settings in multiple-zone VAVR design through experimental setup or field studies. Exploring the impact of this control setting in the installed cases of VAVR system in actual buildings can bring further insight into optimal control strategies of this design for different applications and climate types. **The aim of this research was to introduce some practical guidelines for efficient operation of**

existing commercial buildings with current embedded control platform. Upgrading the control platform of HVAC system in building and employing CO_2 or other building occupancy sensors could bring further opportunities in efficient operation of building.

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Tables

Table 1 Specific load characteristics and ventilation requirements of different building applications

Application	**Outdoor control ventilation, L/s.m^2**	**Sizing ventilation, L/s.m^2**	**Floor area per person, m^2/person**	**Lighting (W/m^2)**	**Electric equipment (W/m^2)**
Office buildings	Sum of 0.00001 L/s/person and 0.43 L/s/m^2	0.43	18.579	8.83	8
Retail establishments	Sum of 0.00001 L/s/person and 1.18 L/s/m^2	1.18	6.193	15.5	3.23
Educational facilities	Sum of 4.7 L/s/person and 0.6 L/s/m^2	2.39	2.654	13.35	10

Table 2 Specific construction characteristics of buildings in different climate types

City	**Climate type**	**Roof insulation, thermal resistance R, m^2.K/W**	**Exterior wall insulation thermal resistance R, m^2.K/W**	**Window specification, U factor and solar heat gain coefficient**
Miami	Tropical monsoon	3.47	1.04	U factor = 0.60, SHGC = 0.25

Phoenix	Hot desert	4.32	1.71	U factor = 0.60, SHGC = 0.25
San Francisco	Mediterranean	4.32	1.9	U factor = 0.55, SHGC = 0.25
Chicago	Humid Continental	5.31	2.82	U factor = 0.48, SHGC = 0.40

Figure Captions

Fig. 1 Schematic diagram of a multiple-zone VAVR

Fig. 2 Inward and outward heat and mass flows for each thermal zone

Fig. 3 The 3D geometry and floor plan of the simulated five-storey building

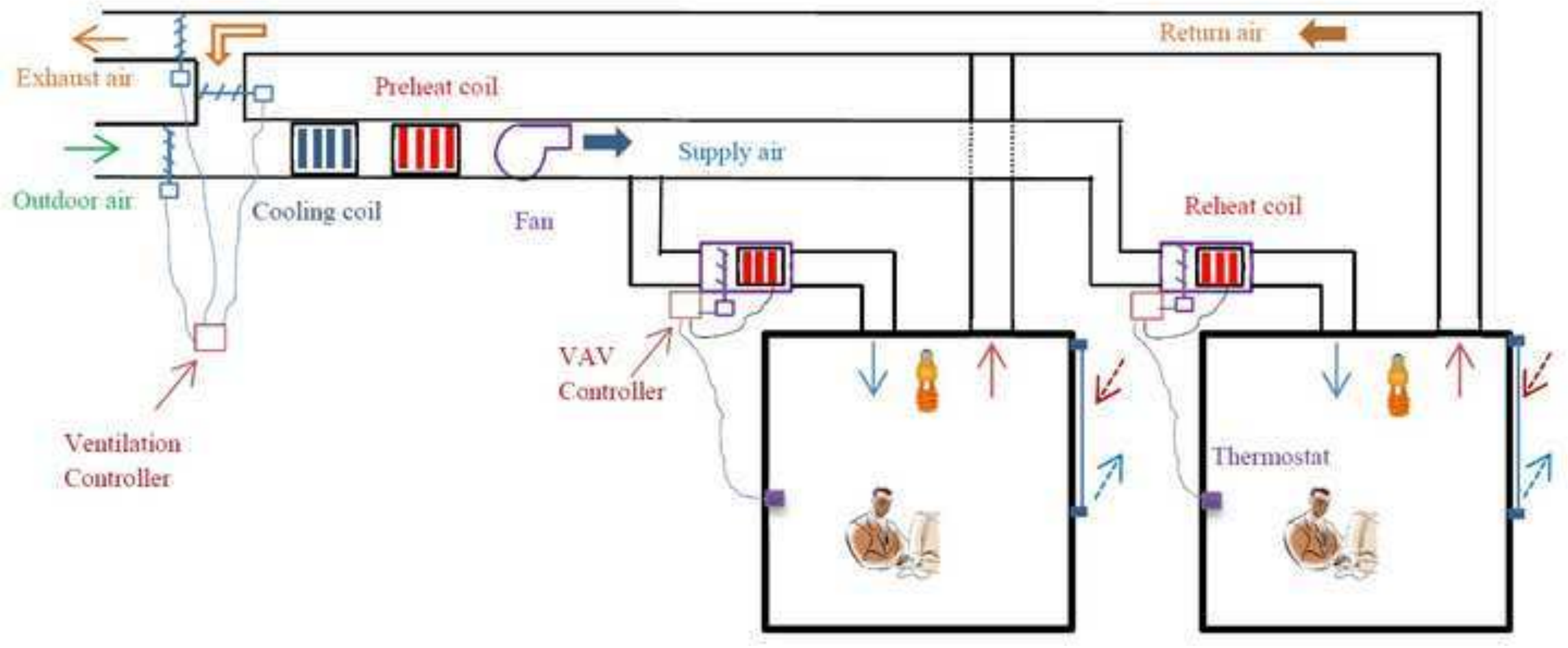
Fig. 4 Comparison of performance metrics in school buildings for the range of MAFF values in (a) tropical monsoon, (b) hot desert, (c) Mediterranean, (d) humid continental climates

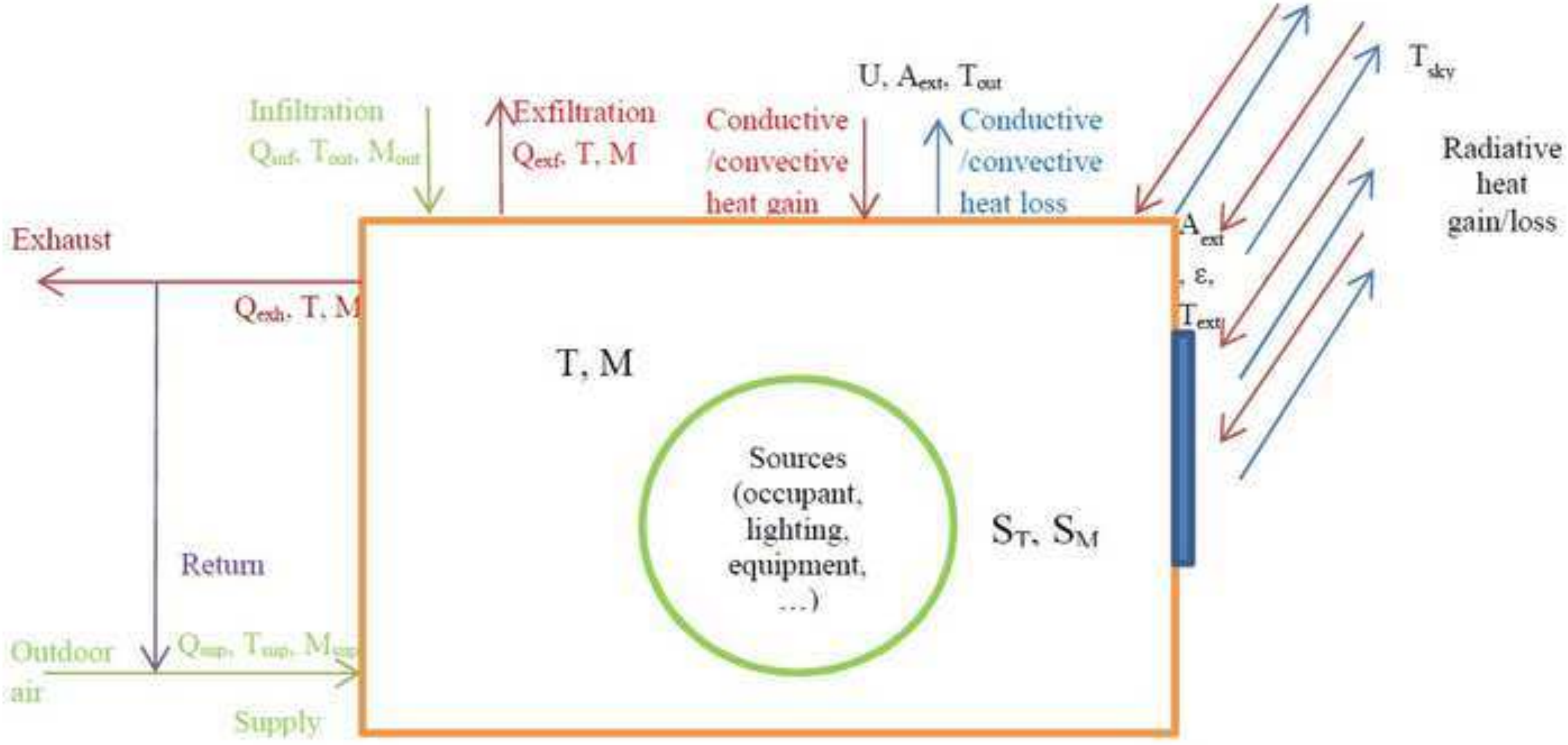
Fig. 5 Comparison of performance metrics in office buildings for the range of MAFF values in (a) tropical monsoon, (b) hot desert, (c) Mediterranean, (d) humid continental climates

Fig. 6 Comparison of performance metrics in retail buildings for the range of MAFF values in (a) tropical monsoon, (b) hot desert, (c) Mediterranean, (d) humid continental climates

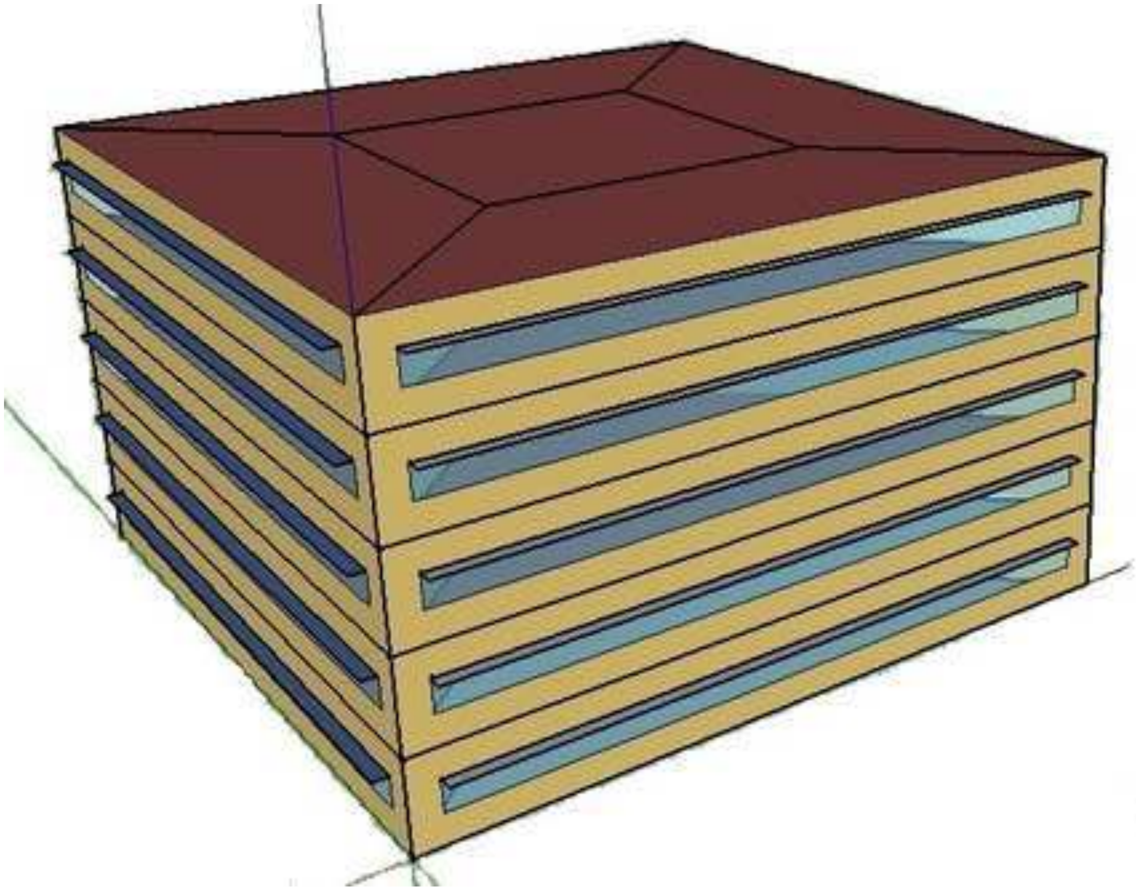
Fig. 7 Comparison of outdoor air flow fraction (OAFF) for the range of MAFF values in different building applications and climate types

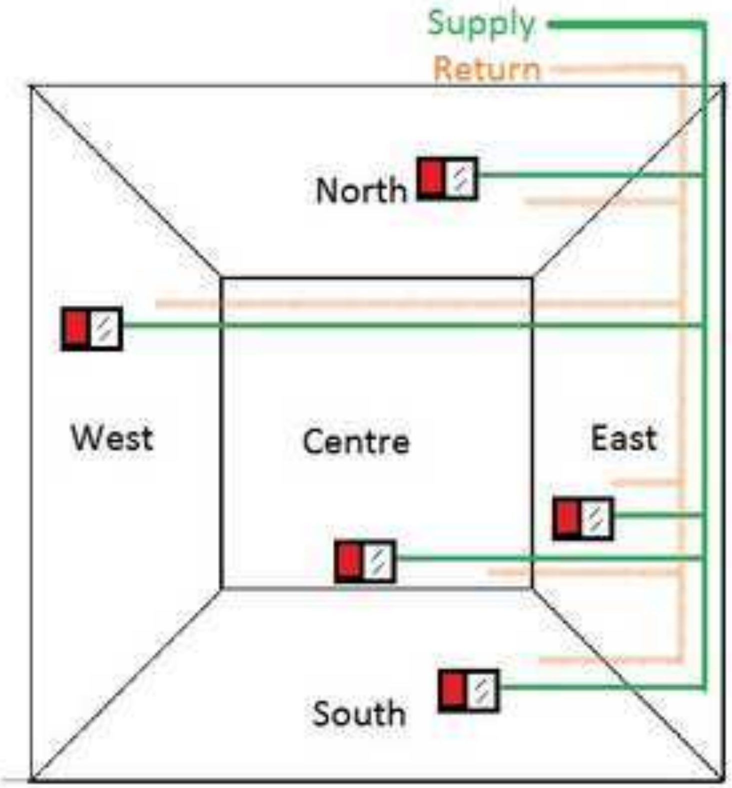
Fig. 8 Flood plot of OAFF over the simulation time for school, office and retail buildings in the tropical monsoon climate of Miami


Exhaust air
Outdoor air
Preheat coil
Cooling coil
Fan
Supply air
Return air
Reheat coil
Ventilation
Controller
VAV
Controller
Thermostat

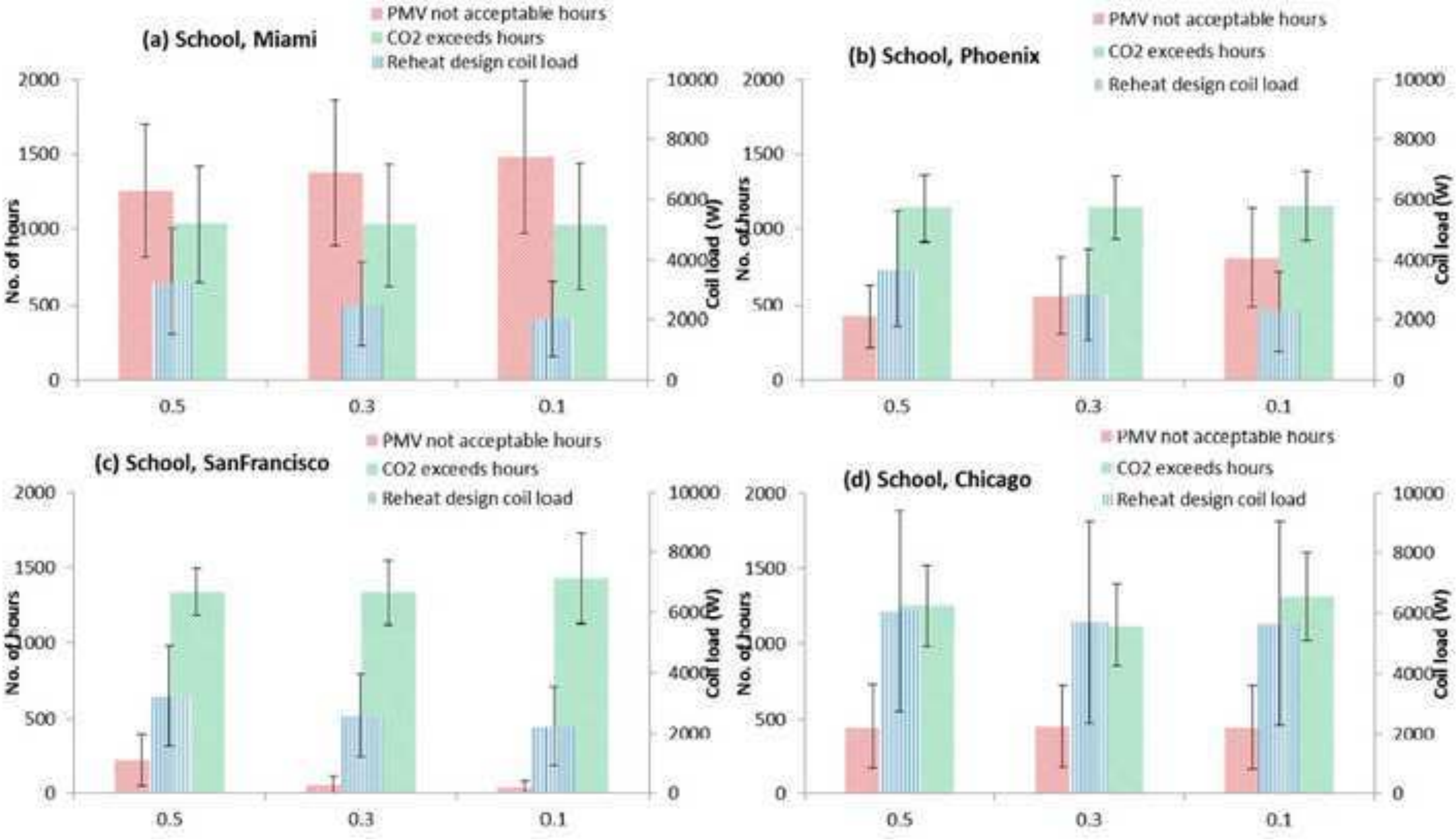


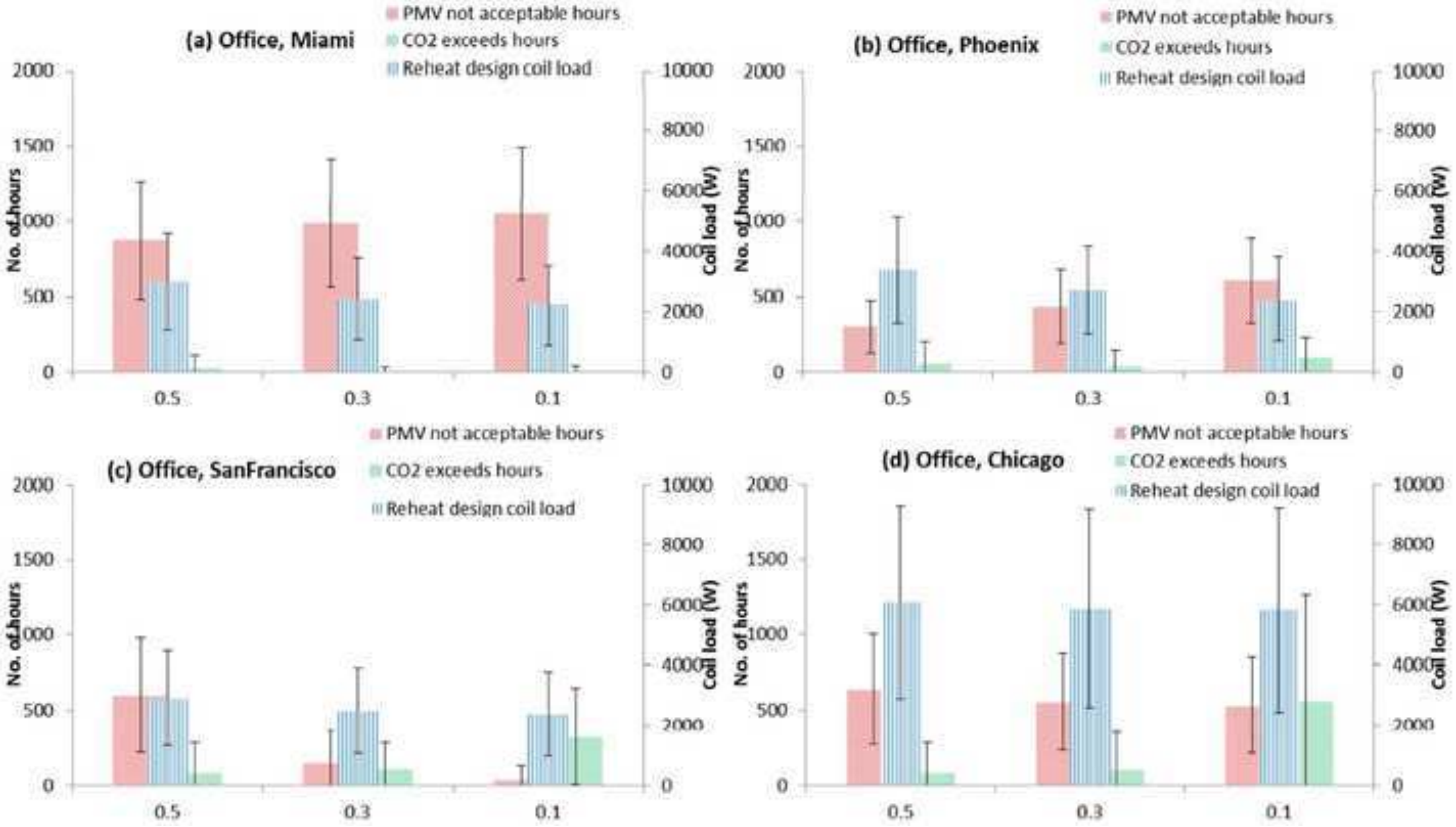
Infiltration
Q_{inf}, T_{out}, M_{out}
Exfiltration
Q_{exf}, T, M
Conductive /convective heat gain
U, A_{ext}, T_{out}
Conductive /convective heat loss
T_{sky}
Radiative heat gain/loss
A_{ext}, ε, T_{ext}
Exhaust
Q_{exh}, T, M
T, M
Sources (occupant, lighting, equipment, …)
S_T, S_M
Return
Outdoor air
Q_{sup}, T_{sup}, M_{sup}
Supply

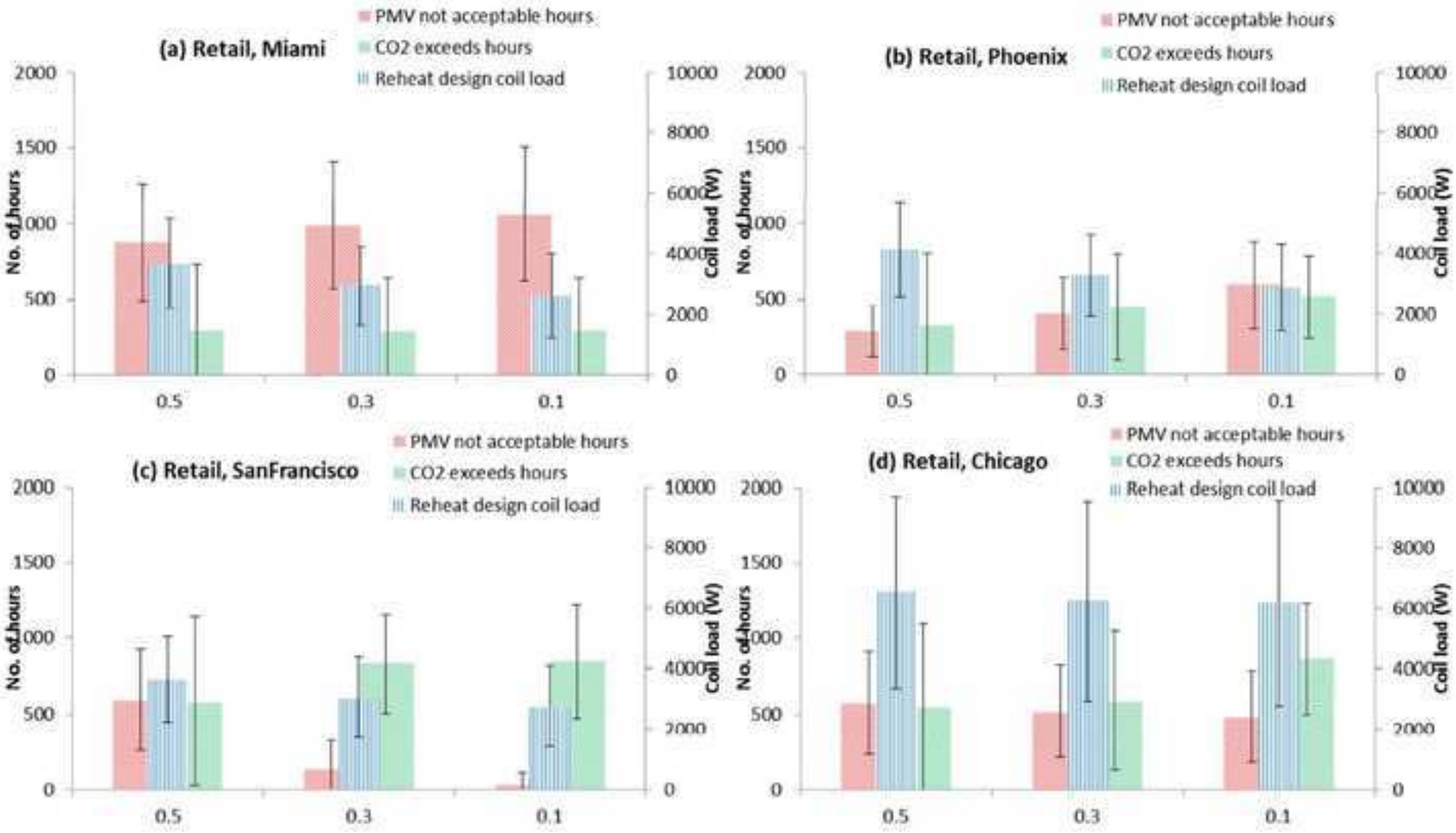


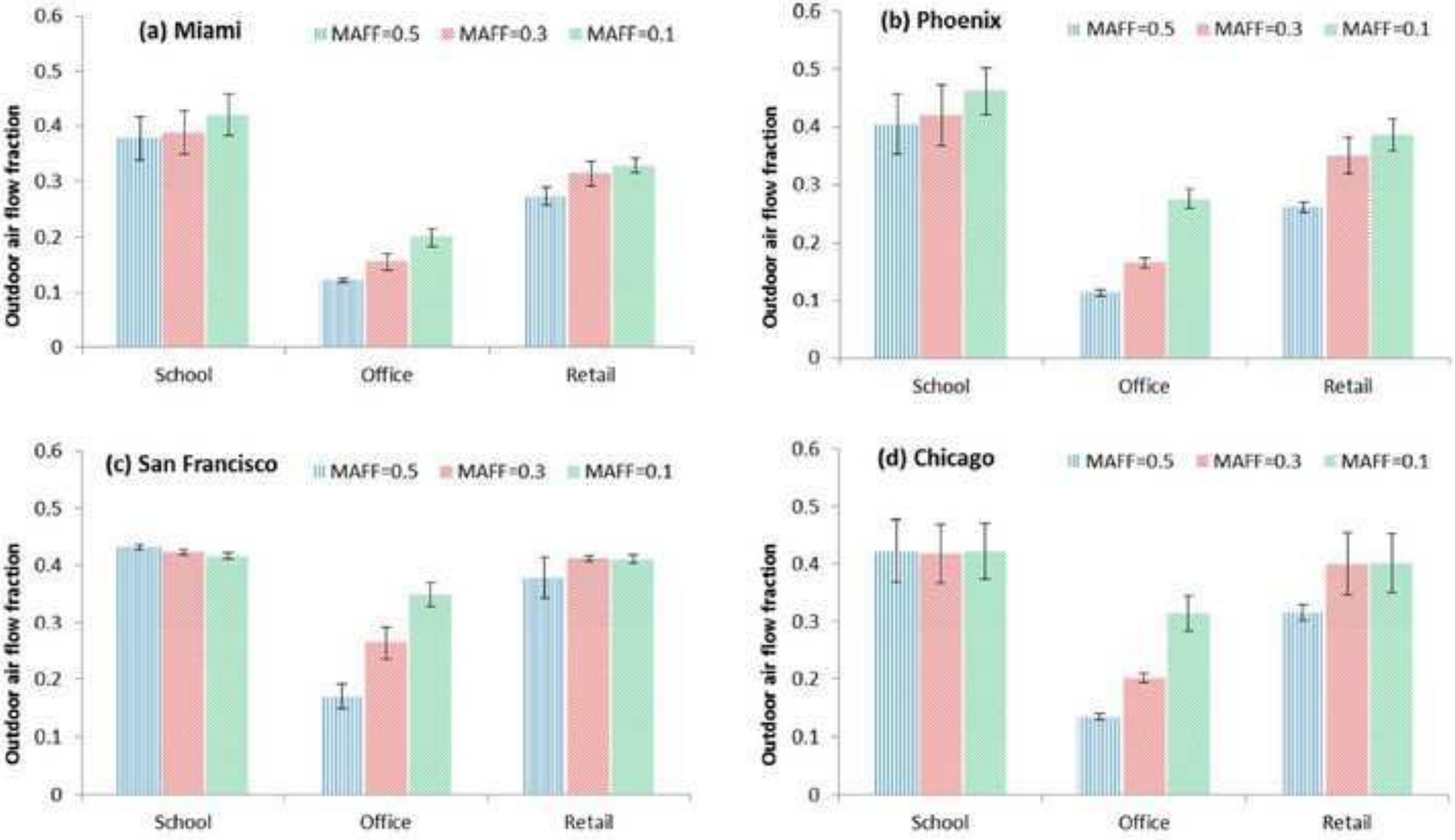


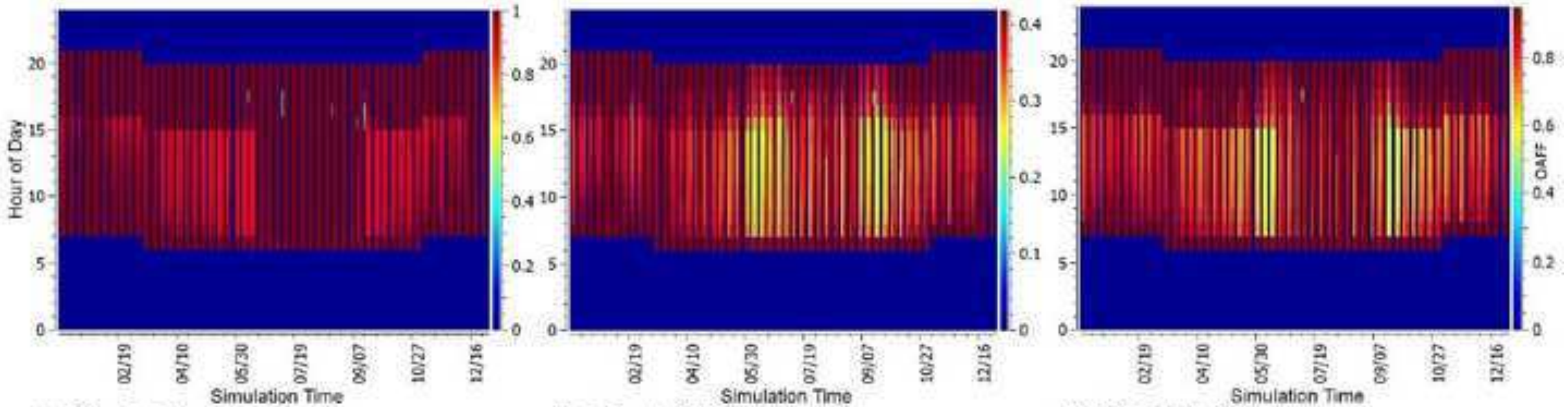
Supply
Return
North
West
Centre
East
South


(a) School, Miami
(b) School, Phoenix
(c) School, SanFrancisco
(d) School, Chicago
PMV not acceptable hours
CO2 exceeds hours
Reheat design coil load
No. of hours
Coil load (W)
0
500
1000
1500
2000
0
2000
4000
6000
8000
10000
0.5
0.3
0.1


(a) Office, Miami
(b) Office, Phoenix
(c) Office, SanFrancisco
(d) Office, Chicago
PMV not acceptable hours
CO2 exceeds hours
Reheat design coil load
No. of hours
Coil load (W)
0
500
1000
1500
2000
0
2000
4000
6000
8000
10000
0.5
0.3
0.1


(a) Retail, Miami
(b) Retail, Phoenix
(c) Retail, SanFrancisco
(d) Retail, Chicago
PMV not acceptable hours
CO2 exceeds hours
Reheat design coil load
No. of hours
Coil load (W)
0
500
1000
1500
2000
0
2000
4000
6000
8000
10000
0.5
0.3
0.1


(a) Miami
(b) Phoenix
(c) San Francisco
(d) Chicago
MAFF=0.5
MAFF=0.3
MAFF=0.1
Outdoor air flow fraction
0
0.1
0.2
0.3
0.4
0.5
0.6
School
Office
Retail



(a) Miami.School (b) Miami.office (c) Miami.Retail