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DESIGN AND TESTING OF A CONTROL STRATEGY FOR A LARGE, NATURALLY VENTILATED OFFICE BUILDING

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ABSTRACT

The design for the new Federal Building for San Francisco includes an office tower that is to be naturally ventilated. Each floor is designed to be cross-ventilated, through upper windows that are controlled by the building management system (BMS). Users have control over lower windows, which can be as much as 50% of the total openable area. There are significant differences in the performance and the control of the windward and leeward sides of the building, and separate monitoring and control strategies are determined for each side. The performance and control of the building has been designed and tested using a modified version of EnergyPlus.

Results from studies with EnergyPlus and CFD are used in designing the control strategy. EnergyPlus was extended to model a simplified version of the airflow pattern determined using CFD. Wind-driven cross-ventilation produces a main jet through the upper openings of the building, across the ceiling from the windward to the leeward side. Below this jet, the occupied regions are subject to a recirculating airflow. Results show that temperatures within the building are predicted to be satisfactory, provided a suitable control strategy is implemented uses night cooling in periods of hot weather.

The control strategy has 10 window opening modes. EnergyPlus was extended to simulate the effects of these modes, and to assess the effects of different forms of user behavior. The results show how user behavior can significantly influence the building performance.

INTRODUCTION

The control system development study presented in this paper continues previous work (Haves *et al*, 2003) on the design of the natural ventilation system for the new San Francisco Federal Building (SFFB). The definition of the control strategy for the natural ventilation system is critical to achieving good performance in the building. The requirements for this control strategy are:

- ability to control air speed in the occupied space;
- effective use of the building internal thermal mass for cooling;
- rational use of heating energy;
- control of indoor conditions during storm, rain and high wind periods;
- unintrusive and as simple as possible.

COMPONENTS OF THE INDOOR CLIMATE CONTROL SYSTEM

Figure 1 shows a section of a typical floor of the naturally ventilated portion of the building. In an earlier phase of the work, reported in a companion paper (Haves et al, 2003), it was determined that the favorable wind climate that exists in San Francisco produces sufficient cross-ventilation to maintain acceptable comfort. During episodes of hot weather, the building is ventilated at night to cool the exposed concrete ceiling slab, which serves as a heat sink for daytime heat gains. Buoyancy forces have a minor effect on the airflow in cooling mode.

Heating is provided by a perimeter baseboard system. There are nine trickle vents under selected baseboards on each bay, on each side of each floor. The main NW and SE facades are ~100% glazed. Although the windows on the SE façade are shaded by an external metal scrim, there is a significant amount of passive solar heating from these windows at the beginning of the day.

The building is controlled by a combination of user and automated window operation. The BMS has exclusive control over the baseboard heating system. As discussed below, the users can significantly change the total opening area, affecting the results of the automated control actions exerted by the BMS. In order to avoid continual control actions, which may be distracting for the occupants and cause unnecessary wear, the BMS will make adjustments approximately every 10 minutes. The exact interval will be determined as part of the process of commissioning the building.

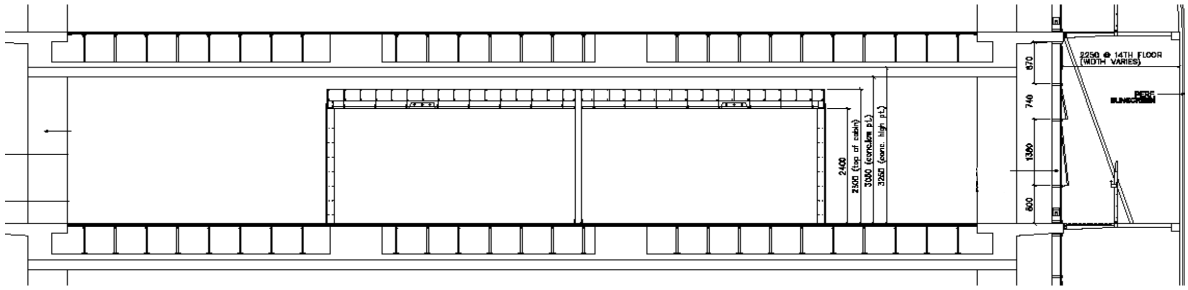


Figure 1. Section of a typical floor of the SFFB.

A section showing the NW bay (left), the SE bay (right) and the air-conditioned meeting rooms (middle). The lower operable windows visible in both bays are controlled by the users. The upper windows are controlled by the BMS. The user operated windows open 10cm, the BMS operated windows open 20cm. There are two user operated windows for every BMS operated window. There is a perforated stainless steel shading scrim that covers the South-East façade of the building.

VENTILATION STRATEGY

Whenever the wind-induced pressure is higher on one side of the building, air will flow into that side and out of the opposing side. The previous natural ventilation airflow analysis revealed an important characteristic of the crossflow ventilation (CV) airflow pattern. The incoming air attaches to the ceiling and partially "short circuits" the occupied zone of the windward bay, exiting through the windows in the leeward facade.

The proposed geometry of the user operated windows contributed to this short circuit effect, generating an inflow jet that attached to the windward user windows and joined the jet entering through the windows operated by the BMS. As a result, the windward side (WS) users had limited control over their local environment. This problem was addressed by proposing changes to the geometry of the user operable windows based on a CFD analysis of the airflow through the window (Linden *et al*, 2002). A flow deflector, which directs the inflow from these openings into the occupied zone, was introduced. The flow pattern produced by the initial design resulted in leeward side (LS) users suffering the consequences of the control actions taken by WS users. With the WS users able to adjust their local flow conditions, by opening and closing a window that directs flow to their work area, the BMS can more easily address the needs of the LS users, using the short circuit of the air entering through the upper windows to produce a beneficial independence between the two sides (see Figure 2).

In addition to this separation, and as a result of the approximately symmetrical layout of the floor plan, we decided to simplify the control strategy by defining it in terms of Windward and Leeward, as opposed to NW and SE. Table 1 shows the four possible states that result from this approach. By basing the control system on the wind direction, the number of system states is significantly reduced.

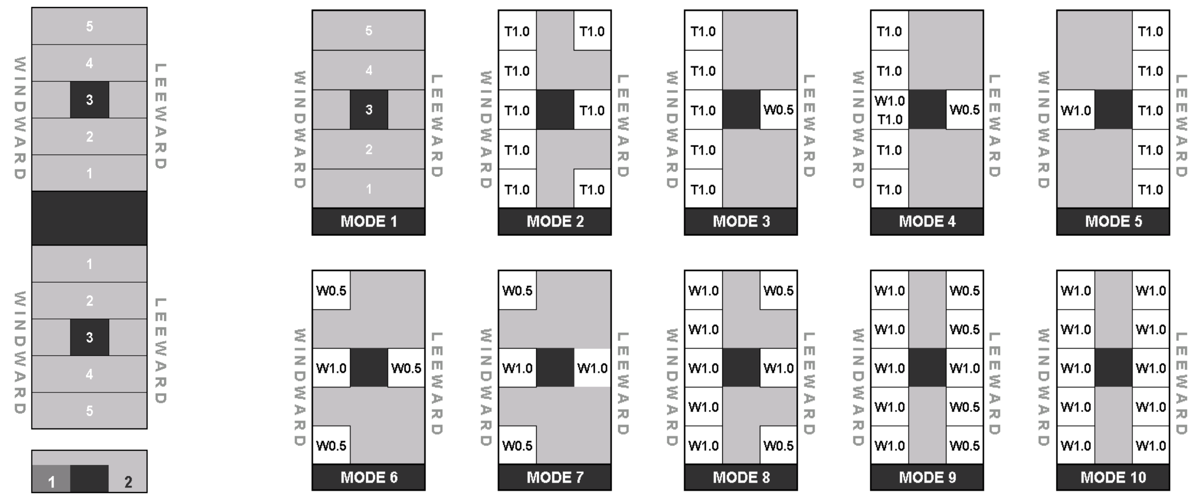
Care was taken to avoid air that had been heated by the baseboard system on the leeward side being exhausted through the adjacent trickle vents. For this reason, whenever the heating is on, only the trickle vents on the windward side are opened. Since height between the BMS and user operable windows is modest, stack driven ventilation is only important when the wind velocity is very low or parallel to the long axis of the building and the trickle vents are open.

Table 1. The four possible states of the occupied spaces on a particular floor during building operation hours.

WINDWARD	LEEWARD
Warm	Warm
Cold	Cold
Cold	Warm
Warm	Cold

Figure 2a shows the floor subdivision used to define the control zones. The basic control unit is one half of a floor (each floor has two BMS zones, one for each set of five "slices", numbered 1-5 in Figure 2a. The labels: W and T stand for window (user operable) and trickle vents (under the baseboard system). The window opening strategy reflects the fact that the geometry of the inflow openings governs the airflow distribution and the consequent effectiveness of the removal of pollutants across the whole width of each side of the naturally ventilated part of the floor. The criteria used in defining the opening modes were:

- use distributed inflow openings to spread the inflow across the floor plan and reduce local velocities;



(a) (b)

Figure 2.

a) Schematic layout of the control system on a typical floor. Each floor measure approximately 107x19m. Each half of each floor in the building is treated separately (in the figure, each set of 1-5 "slices"). Each slice contains four user operated and two BMS operated windows. The side view at the bottom of the figure shows the control structure, using the partial short circuiting of BMS window inflow into the windward zones (labeled 1). b) Schematic representation of the aperture modes. Each floor of the building is divided into two symmetrical sides. The figures show one half of one floor. The black square in the center of the figures is an elevator/service core that creates an obstruction to cross-ventilation airflow.

- use the outlet area to control the flow rate;
- minimize operation of openings (by ensuring continuity between opening modes, avoiding open-close-open sequences as the system increases opening area);
- minimize the number of window positions, in order to simplify the mechanical actuator system (three positions are used: closed, half-open and fully open).

The airflow control strategy was structured in an opening mode table, and the twenty BMS operable windows in each bay of the floor (two per "slice", five "slices" on each side, leeward, windward), were grouped for simplicity. The grouping criterion was optimal flow distribution. Figure 2b shows a schematic representation of the ten opening modes used. The positions of the openings are shown as fraction of maximum opening size (between zero and one).

There are two groups of trickle vents on each bay: "slices" 1, 3 and 5, and "slices" 2 and 4. The window groups are: Group 1 containing the two motorized windows in slice 3, Group 2 contains the four motorized windows in slices 1 and 5 and Group 3 contains the four motorized windows in slices 2 and 4. Modes 3 and 4 use the windows on the leeward side, in slice 3, to avoid exhaustion of warmed air through the leeward side trickle vents.

A mode table was organized in order to contain the opening modes ordered by effective opening area and weather/defensive criteria (see Tables 2 and 3 for grouping and characteristics of the modes). In Table 2, the column labeled "Open" refers to effective opening area. For a given pressure difference (ΔP), the effective opening area A* and resultant flow rate are given by

$$F = A^* C_D \sqrt{\frac{2\Delta P}{\rho}}, \qquad (1)$$

where
$$A^* = \sqrt{\frac{A_W{}^2 A_L{}^2}{A_W{}^2 + A_L{}^2}}.$$

The estimates of the indoor ventilation parameters A_W/A_L, V_{IN} and V_{OZ} presented in Table 2 show that the system has the desired characteristics, listed above. There is a continuous increase in opening size in each group of modes (see Tables 2 and 3). There is a set of modes that controls the inflow and average occupied zone velocities (Modes 5-8); Modes 9 and 10 are meant to be used when the wind is weak, or at night, when significant transfer between indoor air and the ceiling concrete slab is desirable.

Table 2. Characteristics of the opening modes. A_W is the opening area on the windward side, A_L is the opening area on the Leeward side, V_{IN} is the average velocity at the inlet on the windward side, using (1), for a 10m/s outside wind, a pressure coefficient of one and a discharge coefficient C_D of 0.6), V_{OZ} is the predicted average velocity in the occupied zone (from CFD, for a 10m/s outside wind and a pressure coefficient of one), and Open is the ratio of the effective opened area to the maximum effective area,

Mode	A_W/A_L	V_{IN} (m/s)	V_{OZ} (m/s)	Open (%)
1	-	-	-	0
2	2.0	2.7	0.89	3.4
3	0.5	-	-	6.7
4	1.3	3.8	-	22.2
5	3.7	1.6	0.53	7.3
6	4.0	1.5	0.50	13.7
7	2.0	2.7	0.89	25.3
8	2.5	2.3	0.76	52.5
9	1.7	3.1	1.02	72.8
10	1.0	4.3	1.42	100

Although the users have access to operable openings, it was decided that the BMS system would ensure 50% of the regulatory minimum outside air flow. The remainder will be provided by infiltration and the users, through their operable windows. Consequently, upper and lower limits are placed in the opening mode number depending on limiting factors: a lower limit is used in order to ensure minimum outside air, an upper limit is used whenever the wind is strong, during rain periods or when the baseboard heaters are turned on in both bays.

The first high wind opening limiting mode is triggered by:

> *If* $\Delta P>60$ or Vwind>20m/s *then* the mode number cannot go above 8.

The second high wind opening limiting mode is triggered by:

> *If* $\Delta P>130$ or Vwind>25m/s *then* the mode number cannot go above 6.

The storm mode is triggered by:

> *If* $\Delta P>300$ or Vwind>30m/s *then* the mode number cannot go above 2.

Additional rules include:

> *If* heating is on in both bays, *or* it is raining *then* the mode number cannot go above 4.

> *If* both sides are in cooling mode *then* the mode number cannot go below 5.

Table 3. Division of the ten modes in three groups.

Situation	MODES
Storm	1 , 2
Heating/Rain	3 , 4
Mild/Cooling	5 , 6 , 7 , 8 , 9 , 10

INSURING MINIMUM OUTSIDE AIR

With the objective of having the BMS system ensure 50% of the minimum outside air, we establish a decision process based on:

1. the measured the outside pressure difference ΔP;
2. an estimate of stack pressure (whenever the trickle vents are open, in the current control system, this is equivalent to the heating being turned on, see modes 2-4 in figure 1);
3. the fluctuating wind velocity pressure (in order to prevent excessive opening size when the wind is parallel to the building and the average pressure difference measurement (ΔP) is close to zero but the transient ventilation is significant).

The BMS estimates the total available pressure and determines the minimum opening size and the corresponding mode numbers between 3 and 10. When there is a storm (the system is in Modes 1 or 2) we rely on infiltration and user adjustment to provide minimum outside air. Buoyancy will only be considered when the heating is on in both bays (which implies the trickle vents are open).

The total pressure difference (ΔP_T) available to drive the flow is the sum of the pressures discussed above

$$\Delta P_T = \Delta P + HOF\left(0.088\left|\frac{T_W - T_L}{2} - T_{OUT}\right|\right) + 0.015\ U_{WIND}^{\ 2} \quad (2)$$

where U_{WIND} is the outside wind speed and HOF is a software "flag" that signals the buoyancy component should be considered.

The third term in (2) is based on an experimental correlation for airflow in a building exposed to an incoming wind parallel to equal openings on opposed envelope surfaces (Etheridge, 1979). In order to simplify the estimation of ΔP_T, the effects of unequal opening areas on the two bays are ignored. In addition the transient pressure (third) term is not dependent on wind direction. This is an acceptable approximation because, whenever the wind is not parallel to the openings, the first term is an order of magnitude larger.

IMPACT OF USER WINDOW CONTROL

The user operable window area is approximately equal to the BMS controlled area; therefore, users can significantly change the total effective opening area (see (1)). The lower windows are exclusively under user control, and users can, for example, increase the effective opening size ten times when the system is in Mode 5 or approximately double the effective area when in Mode 10.

If user control is not considered when designing the control strategy, two main problems can occur:

(a) users on one of the two sides could significantly affect the climate control on the other side, and

(b) incorrect user control could lead to poor overall system performance, producing overheating of the interior space and concrete slab in summer, and allowing heat to escape to the outside in winter.

The impact of user opening level on the effective opening area decreases with increasing opening mode number. On warm days, whenever the control objective is to make optimal use of the cooled concrete slab, user opening can result in higher, and often uncomfortable, indoor temperatures.

Clearly, the more general consequences of user behavior cannot be addressed by the control system. Therefore, appropriate information on building behavior and on adequate actions in different situations must be provided to the users.

By controlling the airflow rate using the size of the outlet, and by making the flow controlled by WS users affect primarily the WS users, significant automatic control over the conditions of the LS users was achieved. When WS users open their windows, the overall flow does not change significantly if the high level WS windows are already open. However, when these users open their windows, the existing airflow and inflow is partially displaced from the upper (BMS controlled) openings to the user operated windows (in the proportions of the relative opening areas). In this way, the WS users achieve the desired change, more outside airflow through their working area, without significantly changing the leeward side conditions.

However, adjustments by the LS users have a significant effect on the airflow rate. In view of the previously mentioned partial short circuiting of the inflow and the ability of WS users to adjust their local conditions, we conclude that the asymmetry in flow control is a beneficial feature of the system.

MODELING USER BEHAVIOUR

Modeling user behavior is a complex but essential task for the present study. In order to simulate the performance of the indoor environment control system with both BMS and user actions, two types of user behavior were defined.

● Uninformed users (UU): this type of user is modeled so that user behavior is totally independent of BMS actions. If the conditions are warm, the user operable windows open sequentially (10% in each control time step, 10 minutes), up to 50% for indoor temperatures between 22 and 25^{o}C, and up to 100% for temperatures above 25^{o}C. If the conditions are cold, below 19^{o}C, the user operable openings close by 5% each time step. On a typical day, when the air temperature in either of the two bays goes above 22^{o}C, users will open the windows, the windows will then remain open until the temperature on one of the sides drops below 19^{o}C, or until the end of the workday, when users always close their windows.

● Informed users (IU): this type of user follows the BMS actions in an ideal way. Users only open their windows when the BMS is in one of the mild modes. Informed users follow the same decision and action trends as uninformed users but limit their opening amplitude in accordance to the BMS mode that is currently being used (linearly, from 0% in Modes 1-5 to 100% in Mode 10). In addition, whenever the BMS system uses night cooling, informed users will leave their windows fully opened overnight.

These two user behavior scenarios allow us to model overall control system performance (users with BMS) in two extreme situations: positive and negative interaction between users and the BMS system.

CONTROLLING INDOOR TEMPERATURE

Table 1 showed the four temperature states that can occur in the two control zones of the building. We now proceed to describe and analyze the control strategies and rules used in each case.

Both sides cold. When both sides are cold, the heating system is on and the ventilation system will tend to minimum outside air in a progressive way, by reducing the window opening mode by one in each control time step.

Both sides warm. In order to clarify the control principles used during daytime in the warm season, we present here a first order analysis of system behavior. For this analysis we make two approximations.

(i) The only thermally active internal surface is the concrete ceiling slab. This approximation is adequate since the remaining internal surfaces in the space have low thermal mass and, therefore, tend to behave in an approximately adiabatic way, closely following the internal air temperature.

(ii) The internal air is fully mixed in each bay, which is a significant approximation that is only acceptable for a first order analysis. Also, for control purposes, during warm periods, the BMS system uses a single temperature (the highest of the two bays) to represent indoor conditions.

In these conditions, the equation that represents energy conservation in a control zone (one half of one floor, see Figure 2) is

$$h\,A_S\left(T_{IN}-T_S\right)+\rho\,c_P\,F\left(T_{IN}-T_{OUT}\right)=G\,, \qquad (3)$$

where h is the average heat transfer coefficient, T_{IN} is the fully mixed indoor temperature, T_S is the concrete ceiling slab average surface temperature, T_{OUT} is the outside temperature, c_p is the heat capacity of air at constant pressure, ρ is the density of air, F is the volumetric flow rate and G is the sum of the other heat gains (solar, internal and heat conduction through the envelope). The solution to (3) is

$$T_{IN}=\frac{1}{1+\theta}\left(T_S+\theta\,T_{OUT}+\frac{G}{h\,A_S}\right) \qquad (4)$$

where $\theta = \rho c_p F/hA_S$ is the normalized air flow rate.

Once a building is in operation, all the temperatures in this expression can be measured and used to make decisions on the single adjustment parameter available, the flow rate F. The gains, the value of the heat transfer coefficient and exposed area are generally unknown, although, in an office space in mild climate, we expect the gains to be positive during the mild/warm season.

Qualitative analysis of (3) reveals that when F is increased, the parameter θ increases and T_{IN} tends to T_{OUT}. Conversely, decreasing θ brings T_{IN} closer to T_S. The unknown parameter G influences internal conditions (increased G results in increased T_{IN}), but, by measuring T_{IN} we can obtain an indirect measurement of G, and there is no decreased control ability from not knowing the internal gains. Table 4 presents the warm weather control rule map that was used.

Windward cold, leeward warm: as seen in the simulation results below, this situation often occurs in the early morning of the winter and mild season days. This is one of the situations where the interaction between the two sides must be considered. To meet the need for cooling in the leeward side the ventilation mode is increased by one. In order not to increase the cooling needs of the LS users, but still address the need for heating on the windward side, the windward heating set point is set to 18°C.

Windward warm, leeward cold: this case is the contrary of the previous case, but is not as problematic because the WS side users can address their needs by opening their user window (increasing local flow rate) without greatly affecting the overall flow rate. For these reasons, in this situation, the control system will reduce the aperture mode by one and set the leeward heating set-point to a relatively high value (21°C), to ensure heating on this side.

Night cooling: night cooling of the concrete ceiling slab will be done whenever the average indoor temperature during the warmer period of the day (11 am - 4 pm) is above 24°C. When night cooling is requested by the temperature control routine the ventilation system uses the maximum allowed opening mode until the slab temperature is below 19°C or until the early morning of the following day (7 am).

Table 4. Flow rate decision rules as a function of measured temperatures.

Situation	Flow
$T_{IN} > T_{OUT}$, T_S	Increase
$T_{IN} < T_S$, T_{OUT}	Maintain, or increase if cold
$T_{OUT} > T_{IN} > T_S$	Decrease if warm, increase if cold
$T_S > T_{IN} > T_{OUT}$	Increase if warm, decrease if cold

In future, the design team intends to incorporate weather prediction information in the control system, basing the decision to night cool on the next days predicted weather as well heat storage in the fabric during the previous day.

SIMULATION

In order to develop and test the low energy cooling system and its BMS control strategies, the behavior of the building and users was modeled using EnergyPlus, which incorporates the COMIS interzone airflow model (Huang et al, 1999). The model implemented to test the initial design principles (Haves et al, 2003) was the starting point for the model used in the simulations presented below. This model uses four distinct zones: the two bays (NW and SE), the meeting room in the middle of the floor plan and the space above the meeting rooms (see Figures 1 and 2). The simulation used pressure coefficients measured in a boundary layer wind tunnel (RWDI, 2002). Pressure coefficients representative of average wind exposure in the naturally ventilated portion of the building were chosen. Since only floors 6 and above are naturally ventilated, and adjacent buildings do not reach this height, all floors have sufficient wind exposure.

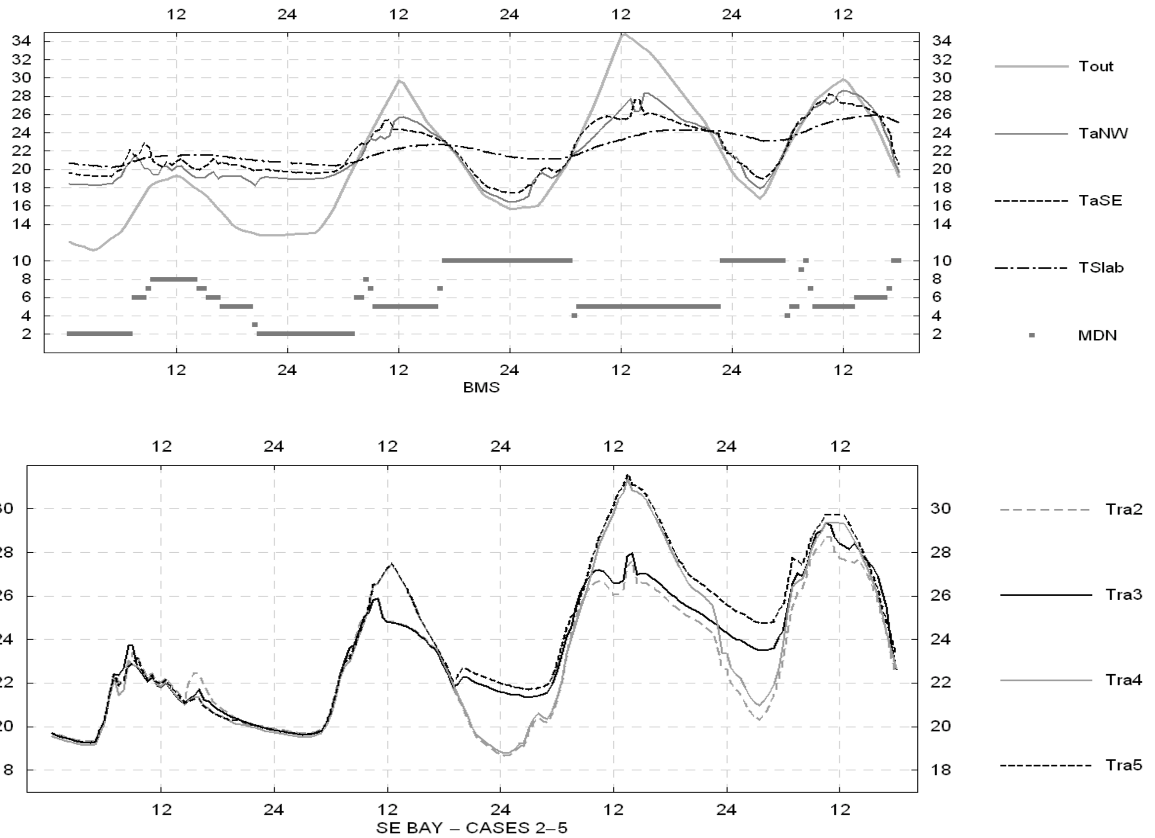


Figure 3. Predicted temperatures for case 1 in a sequence of warm days in July

All temperatures in ^{o}C. Tout: outside air temperature. TaNW: average air temperature in the North West bay. TaSE: average air temperature in the South East bay. TSlab: average surface temperature of the concrete ceiling slab. MDN: BMS system window opening mode. Tra2-5: the mean of drybulb air and mean radiant temperature temperature in the SE bay for cases 2-5.

The modularity of EnergyPlus allowed for the inclusion of a custom control subroutine (a module) that was used to simulate and tune the operation of the BMS system. The transmissivity of the metal shading scrim on the SE façade (see Figure 1) was set to 30%. The five cases simulated are shown in Table 5. Two typical mean weather years for San Francisco where used (a TMY and a TMY2).

Table 5. The five cases tested. First column: case number. Second: whether the case uses BMS control during the day. Third: whether the system uses night cooling. Four: type of user control, informed (IU), uninformed (UU) or no opening of the user operated windows.

Case	BMS	Night Cool	Users
1	Yes	Yes	No
2	Yes	Yes	IU
3	Yes	No	No
4	Yes	Yes	UU
5	No	No	UU

RESULTS

Figure 3 shows the predicted temperatures in the two bays and in the surface of concrete ceiling slab, for case 1 during a sequence of warm days in July. The results are plotted as 30 minute averages. The BMS system made decisions (turn on-off heating, change window modes) every 10 min. The first day shows typical behavior in a mild day. Between 10am and 2pm the BMS system uses outside air to remove internal heat gains. The second day is a typical warm day, and the BMS system selects the minimum daytime mild/warm mode (Mode=5). The air temperature in the SE bay (TaSE) has two phases during the day: above TaNW during the morning, as a result of solar gains in the SE façade, and below TaNW in the afternoon as a result of increased slab cooling effect in this bay. For NW incoming wind, the air moves in contact with the ceiling slab until it enters the SE bay. During the unoccupied night period of the second and third days shown, the system performs night cooling by selecting the maximum opening mode (Mode=10). The increase in slab temperature is visible. Temperatures labeled “ra” are the average “comfort” temperature (average of the mean radiant and air temperatures) in the two bays. As expected, air flows from NW to SE for a majority of the hours. The consequence of change in airflow direction is clearly visible at 1pm on the third day. As a result of a wind direction change the mean of drybulb air and mean radiant temperature changes, with a consequent increase in the SE as airflow cooled by the slab is replaced by warmer outside air.

Table 6 presents indicators of indoor climate control system performance for the five cases shown in Table 5. It is clear that uninformed users (cases 4 and 5) can have a significant negative impact in indoor climate conditions. According to our assumptions, uninformed users make limited use of the cooled slab and consequently warm their indoor environment. Because these conditions are not frequent, there is no substantial impact on system performance. Since the user operable area is comparable to the BMS controlled area, the impact extends to case 4. The absence of night cooling results in a 1K increase in the temperature on the warmest days.

Table 6. Percentage of hours during daytime operation schedule that are above 24, 26, 28 and 30^{o}C.Columns labeled NW and SE refer to the two building bays. The cases correspond to those listed in Table 5.

Case	H >24^{o}C NW	SE	H >26^{o}C NW	SE	H >28^{o}C NW	SE	H >30^{o}C NW	SE
1	2.2	14	0.6	2.5	0.12	0.64	0.00	0.18
2	2.2	12	0.7	2.2	0.17	0.64	0.00	0.19
3	3.9	19	1.0	4.1	0.29	0.95	0.00	0.30
4	2.9	10	1.2	2.4	0.45	0.96	0.11	0.38
5	4.2	16	1.4	4.2	0.52	1.3	0.16	0.49

CONCLUSIONS

The results of the simulations show that the low energy indoor climate control system developed is expected to have excellent performance. The use of a window aperture mode table, in conjunction with the Windward-Leeward based control strategy, resulted in a clear and effective natural ventilation system. Analysis using simple heat balance calculations provides a basis for the simple temperature control strategy adopted.

Night cooling and optimal use of the chilled slab during the day is an appropriate strategy to deal with the warmest periods. As a result of the significant user controlled aperture area, the more general consequences of user behavior cannot be addressed by the control system. Clearly, information for the users on building behavior and on appropriate actions in different situations is important. However, simulations of different control strategies showed that the operation of the BMS always improves indoor conditions, even when occupant behavior is counterproductive.

ACKNOWLEDGEMENTS

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