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Design and testing of a control strategy for a large, naturally ventilated office building

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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 computational fluid dynamics (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 that 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.

1 Introduction

The control system development study presented in this paper continues previous work[1,2] on the design of the natural ventilation system for the new San Francisco Federal Building (SFFB). The present study, which determines the optimal control strategy for the low energy cooling system, is a fundamental component in the achievement of maximum performance of the passive cooling system.

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The control strategy described in this paper is part of an effort to create a low energy indoor climate control system, or building management system (BMS), with the following characteristics:

- ability to control indoor airflow velocities
- effective use of the building internal thermal mass for cooling
- rational use of heating energy
- ability to control indoor conditions during storm, rain and high wind periods
- unobtrusive and as simple as possible.

This paper begins in Section 1 with a description of the components of the indoor climate control system. The cross-ventilation air flow

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is described in Section 3, which considers the impacts of the user controlled windows. The control modes are defined in Section 4. This includes the rationale for the choice of the modes and the definition of the building in terms of its windward and leeward sides. The simulations are described in Section 5 and the results are given in Section 6. Conclusions are drawn in Section 7.

2 Components of the indoor climate control system

Figure 1 shows a section across a typical floor of the naturally ventilated portion of the building. As shown in our previous study,[1,2] use of the stack effect to supplement wind-driven flow does not improve the cooling performance of the building significantly, given the favourable wind climate that exists in San Francisco. The design uses wind-driven cross-ventilation to cool and remove pollutants from the open-plan spaces.

Wind enters through windows on the NW and SE facades. The upper windows are controlled by the building management system (BMS) and the lower windows are controlled by the users. The orientation of the building is such that the usual flow is from the NW bay to the SE bay (see Figure 1). This wind-driven flow provides the main cooling in the warm season, either directly during the day or by night time precooling of the ceiling slab. The aim of this study is to develop a strategy for controlling the windows so that desired indoor temperatures are maintained throughout the year.

Heating is provided by a perimeter baseboard system. There are nine trickle vents under selected baseboards on the exterior wall of each bay. When there is need, and the outside temperature allows it, outside air can also be used to warm the building. Essentially all of the SE façade is glazed. Although these windows are shaded by an external metal scrim (see Figure 1) there is a significant amount of passive solar heating through these windows at the beginning of the day.

The cooling source is the outside environment either by direct daytime heat removal using ventilation air, or through an exposed concrete ceiling slab that can be cooled during unoccupied hours using outside air. This cooled thermal mass can be used as a heat sink for daytime gains (the standard night cooling principle), both to reduce maximum indoor temperatures and to delay the time of the maximum temperature until after the end of the working day.

The building will be controlled by a combination of user and automated window

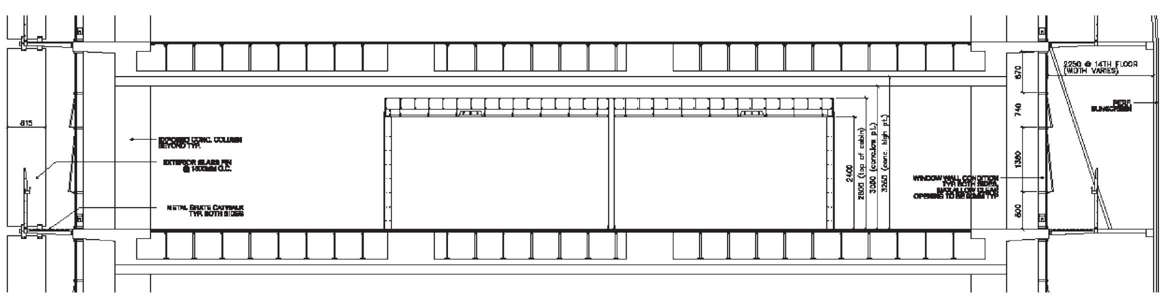

Figure 1 Section of a typical floor. A section from the NW bay (left) to the SE bay (right), showing the air-conditioned meeting rooms in the center. The lower operable windows visible on both bays are controlled by the users. The upper windows are controlled by the building management system (BMS). The user operated windows open 10 cm, the BMS operated windows open 20 cm. There are two user operable windows for every BMS operated window. The metal shading scrim that covers the South east façade of the building is shown on the right

adjustment. The automated building management system (BMS) has exclusive control over the baseboard heating system. As will be discussed in Section 6, the users can significantly change the effective opening area, affecting the result of the BMS decisions. In order to avoid continuous, possibly distracting and wasteful, control actions, the BMS will make adjustments, heating set points, window positions, every 10 minutes. This time interval is discussed below and may be adjusted when the building is commissioned.

3 Optimal cross-ventilation airflow

The basic ventilation is wind-driven cross ventilation from the windward side to the leeward side of the building. Usually, but not always, the NW façade is at positive pressure and inflow occurs on that side of the building. The control strategy uses pressure data to determine the windward side (WS) and leeward side (LS), which, of course, depends on the actual wind direction. The controls are based on the instantaneous WS and LS designation.

The CFD analysis of the natural ventilation airflow, performed by Linden and Carrilho da Graça[1] showed that the inflow air attaches to the ceiling and partially 'short circuits' the windward bay, exiting through the windows in the leeward bay. The initially proposed geometry of the user operated windows contributed to this effect by generating an inflow jet that attached to the WS user windows and joined the BMS operated window inflow jet. Under these conditions the WS users had limited control over their environment. To solve this problem, a flow deflector was introduced on the lower windows, which directs the inflow through them into the occupied zone. This allows WS occupants to influence their local environment.

This modification to the window design allows for an elegant approach to the cross-ventilation control strategy, since it disrupts the pure sequential organization of the airflow from windward to leeward. This initial flow pattern caused LS users to be strongly affected by the control actions taken by WS users. With WS users able to adjust their local flow, by opening or closing a window that directs flow to their work area, the BMS can address the needs of the LS users (see Figure 2).

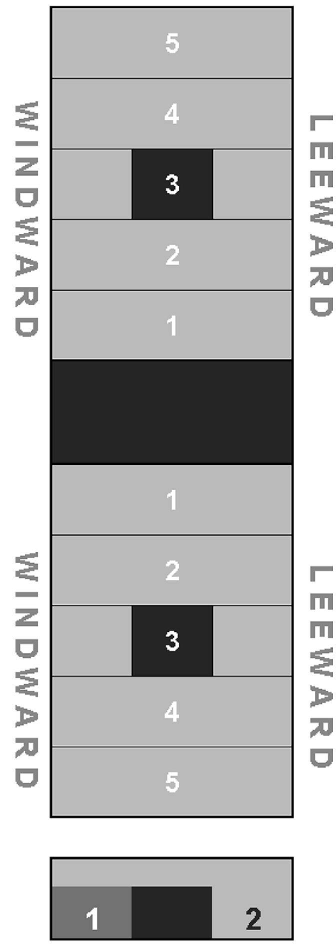

Figure 2 Schematic layout of the control system on a typical floor

In addition to this separation, and as a result of the approximately symmetrical layout of the floor plan, we developed the control strategy using a Windward-Leeward

Table 1 The four possible states of a floor during building operation hours

Windward	Leeward
Warm	Warm
Cold	Cold
Cold	Warm
Warm	Cold

reference system, as opposed to a NW–SE bay reference. This decision is a consequence of the importance of the flow pattern in the system behaviour and our desire to simplify the control system. Table 1 shows the four possible states that result from this approach. By basing the control system on the wind direction the number of possible system states is greatly reduced.

The geometry of the building natural ventilation system, and the dominance of wind versus buoyancy, require special considerations over the opening geometry whenever heating is on. In particular, it is necessary to avoid exhaustion of air, heated by the baseboard system, through the adjacent trickle vents on the leeward side. For this reason, whenever the heating is on, only the trickle vents on the windward side will be opened. Since the BMS and user operable windows are close in height, stack driven ventilation is only important when the wind velocity is very low or perpendicular to the building cross-ventilation axis and the trickle vents are opened.

Figure 2 shows the floor subdivision used to define the controlled zones. The basic control unit or subdivision is one half of the floor shown (each floor has two BMS systems, one for each set of five 'slices', numbered 1–5 in Figure 2). The window opening strategy reflects the fact that inflow geometry is the governing parameter in the airflow distribution. Each floor measures approximately 107×19 m. Each half of each floor in the building is treated separately and divided into five slices numbered as shown. Each slice contains four user operated and two BMS operated windows. The side view on the bottom of Figure 2 shows the control structure, using the partial short circuiting of BMS window inflow into the windward zones (labelled 1). The criteria followed when defining the opening modes were:

- use distributed WS inflow openings to distribute the inflow across the floor plan and reduce inflow velocities
- use the LS outlet area to control the flow rate
- minimize operation of openings (by ensuring continuity between opening modes, avoiding open–close–open sequences on a particular window group as the system increases opening area)
- minimize window positions, in order to simplify the mechanical actuator system (three positions are used: closed, half open and fully open).

The airflow control system was structured in an opening mode table, and the 20 BMS operable windows on each bay of the floor (two per 'slice', five 'slices' on each side, leeward and windward) were grouped for simplicity. The grouping criterion was optimal flow distribution. Figure 3 shows a schematic representation of the ten opening modes used. The positions of the openings are shown as fractions of the maximum opening size (between zero and one). There are two groups of trickle vents on each bay: 'slices' 1, 3, 5, and 'slices' 2, 4. The window groups are:

Group 1 — the two motorized windows in slice 3
Group 2 — the four motorized windows in slices 1 and 5
Group 3 — the four motorized windows in slices 2 and 4.

A mode table was written with the opening modes, denoted by the mode number MDN, ordered by effective opening area and

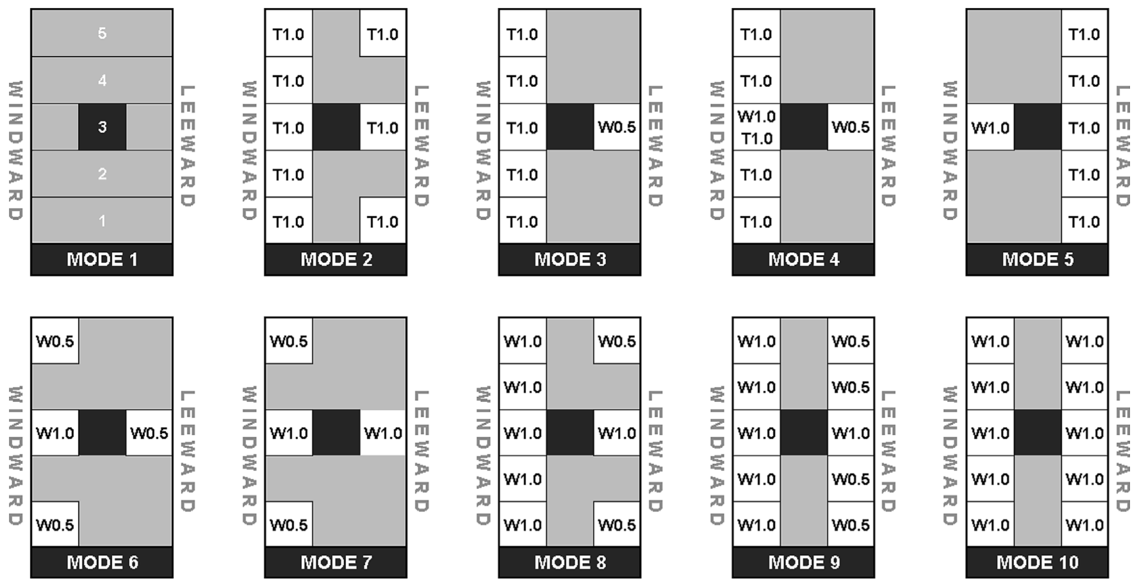

Figure 3 Schematic representation of the aperture modes. Each floor of the building is divided into two symmetrical sides. The figure shows one half of one floor. The black square in the center of the figures is an elevator/service core that creates an obstruction to cross-ventilation airflow

weather/defensive criteria (see Tables 2 and 3 for grouping and characteristics of the modes). This organization allowed for a control strategy that reflects the existence of the several system components mentioned above. On receipt of a request for increased heating or cooling, the ventilation system refers to the opening table and adjusts the flow by incrementing or decrementing the mode number.

Although the users have access to operable windows, it was decided that the BMS system would be used to ensure 50% of the regulatory minimum outside air amount. As a consequence of this decision, and of special outside conditions, upper and lower limits are placed on the opening mode number depending on the following 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 periods of rain or when the baseboard heaters are turned on in both bays.

The modes are organized as follows—also see Tables 2 and 3. First, the modes are divided into storm (MDN 1 and MDN 2), heating (MDN 3 and MDN 4) and cooling modes (MDN 5–10):

When heating is on in both bays *or* it is raining *then* MDN $= 4$.
When both sides are in cooling mode *then* MDN ≥ 5.

Within these subdivisions, the control modes have further constraints at times of high external wind speeds. The first high wind opening limiting mode is triggered by:

If $\Delta P62; 130$ or Vwind $> 20\,\mathrm{m/s}$ *then* MDN $= 8$.

The second high wind opening limiting mode is triggered by:

If $\Delta P > 130$ or Vwind $> 25\,\mathrm{m/s}$ *then* MDN $= 6$.

The storm mode is triggered by:

If $\Delta P > 300$ or Vwind $> 30\,\mathrm{m/s}$ *then* MDN $= 2$.

Table 2 Characteristics of the opening modes

Mode number	A_W/A_L	V_{IN}	V_{OZ}	%*Open*
1	—	—	—	0
2	2	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	1.5	0.50	13.7
7	2	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	4.3	1.42	100

%Open is the effective opened area over maximum effective area. The average velocity V_{IN} at the inlet on the windward side is determined using Equation (1), for a 10 m/s outside wind, a pressure coefficient of 1 and a discharge coefficient (C_D) of 0.6. The predicted average velocity V_{OZ} in the occupied zone is obtained from CFD, for a 10 m/s outside wind and a pressure coefficient of 1. VIN and VOZ are not shown for modes where it was not possible to define or when CFD predictions where not available.

For a given pressure difference (ΔP), the effective opening area A^* and resultant flow rate F is given by:

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

where A_W and A_L are the opening areas on the windward and leeward sides, respectively.

The estimates of indoor ventilation parameters presented in Table 2 show that the system has the desired characteristics, mentioned 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 (MDN 5–8). MDN 9 and MDN 10 are intended to be used when the wind is weak, or at night, when significant transfer between indoor air and the ceiling concrete slab are desirable.

Table 3 Division of the 10 modes into three groups

Situation	Modes
Storm	1, 2
Heating/rain	3, 4
Mild/cooling	5 , 6 , 7 , 8 , 9 , 10

3.1 Insuring minimum outside air

With the objective of having the BMS system ensure 50% of the minimum required outside air, we establish a decision process that starts from:

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

The algorithm estimates the total available pressure and determines the minimum opening size, which is translated into a mode between MDN 3 and MDN 10. When there is a storm (the system is in MDN 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 composed of the sum of the factors mentioned above:

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

where U_{WIND} is the outside wind pressure and HOF is a software 'flag' that signals the buoyancy component should be considered. The third term in Equation (2) is based on an experimental correlation to predict airflow in a building exposed to an incoming wind that is perpendicular to equal openings on opposite facades[4]. In order to keep the ΔP_T estimation simple, the effects of unequal opening areas on the two bays are ignored. In addition, the transient pressure term is not dependent on wind direction; this is an acceptable approximation because whenever the wind is not perpendicular to the openings the first term is one order of magnitude larger.

3.2 Impact of user window control

The lower windows shown in Figure 1 are under exclusive user control. The user operable window area is approximately equal to the BMS controlled area. Therefore, users can significantly change the effective opening area (see Equation (1)). For example, they can increase the effective opening size by a factor of 10 when the BMS is in MDN 1 or approximately double the effective area when it is in MDN 10. If user control is not considered when designing the BMS two main problems can occur:

- users on one of the two sides can affect the climate control on the other side
- incorrect user control can lead to poor system performance, allowing for overheating of the interior space and concrete slab in summer and for heat loss to the outside in winter.

The first of these problems was addressed by making the outlet opening area smaller than the inlet area. From Equation (1) this implies that the effective area is controlled by the size of the outlet rather than the inlet. Figure 4 illustrates the effect of this strategy. The three pairs of lines in Figure 4 show the influence that LS and WS users have on the effective area (and consequently airflow rate). Three different opening areas are shown corresponding to MDN 5, MDN 7 and MDN 9 and the qualitative behavior is the same for each mode. As the amount of WS user area increases, the air flow (shown as the grey lines) remains almost constant. Consequently, the WS users obtain the desired increased local air flow when they open windows, but the effect on the LS users is minimal.

By contrast, adjustments by the LS users have a significant effect on the airflow and, consequently, on their indoor environment conditions (as shown by the black lines in Figure 4). In view of the previously mentioned partial short-circuiting on the inflow and the ability of windward users to adjust their local conditions, we conclude that the asymmetry in flow control is a beneficial feature in the system. The impact of user behavior depends on the state of the BMS. The percentage of user opening on the total effective opening area decreases with increasing mode number. It will be shown later that, on hot days, when the BMS system tries 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 behaviour and on appropriate actions in different situations must be provided to the users.

3.3 Modeling user behaviour

Modeling user behaviour 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 behaviour were defined.

Uninformed Users (UU): this type of user is modeled with behaviour that is independent of BMS actions. If the conditions are warm, the user operable windows open sequentially (10% in each control time step of 10 min), up to 50% for indoor temperatures between 22 and 25°C, and up to 100% for temperatures above 25°C. If the conditions are cold, i.e. below 19°C the user operable windows close by 5% each time step. On a typical day, when the air temperature in either of the two bays goes above 22°C, the users will open the windows. The windows then remain open until one of the sides feels cold (air temperature below 18°C), or until the end of the working day, when users always close their windows.

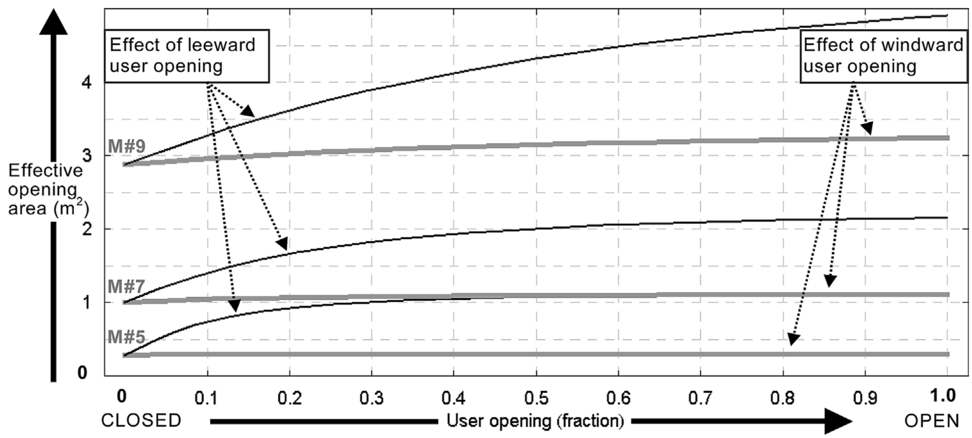

Figure 4 Variation of effective opening area (A^*, expression (1)) with user opening. The three pairs of lines (from bottom to top) show the effective area for, respectively, opening MDN 5, 7 and 9. The grey lines are obtained by varying the user operable opening area on the windward side. The black lines are obtained by varying the user operable opening area on the leeward side

Clearly, under our assumptions, uninformed users do not follow the BMS opening modes at all.

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 weather modes. Informed users follow the same decision and action trends as uninformed users but limit their opening amplitude in accordance with the BMS mode that is currently being used (i.e. linearly, from 0% in MDN 1–5 to 100% in MDN 10). In addition, whenever the BMS system uses night cooling, informed users will leave their windows fully open overnight.

4 Controlling indoor temperature

Table 1 shows 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.

4.1 Both sides cold

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

4.2 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. To make this simple analysis possible we use two approximations.

i) The only thermally active internal surface that will be considered is the concrete ceiling slab. This approximation is adequate since the remaining internal surfaces in the space have low thermal capacity and, therefore, tend to behave in an approximately adiabatic way since both sides are exposed to similar conditions.
ii) The internal air is considered fully mixed. This is a significant approximation only acceptable for a first order analysis. For warm period control purposes we use a single temperature (the higher of the temperatures in the two bays) to regulate indoor conditions.

Under these approximations, the heat balance on a control zone (one half of one floor, see Figure 2) is

$$hA_S(T_{IN} - T_S) + \rho C_P F(T_{IN} - T_{OUT}) = G \tag{3}$$

where h is the convective heat transfer coefficient at the ceiling, T_{IN} is the fully mixed indoor air temperature, T_S is the 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 air density, F is the volumetric ventilation flow rate and G (W) is the total internal gain (solar, internal and heat conduction through the building envelope). The solution to Equation (3) is

$$T_{IN} = \frac{1}{1+\theta}\left(T_S + \theta T_{OUT} + \frac{G}{hA_S}\right), \theta = \frac{\rho C_P F}{hA_S} \tag{4}$$

Once the building is in operation, all the temperatures in this expression can be measured and used to determine whether to increase or decrease the normalized flow rate θ. The values of the heat transfer coefficient and the exposed area are unknown but are positive. Similarly, the heat gain, G, is positive (by definition) during the cooling season.

Qualitative analysis of Equation (3) reveals that when the flow rate, F, and hence the normalized flow rate, θ, is increased, T_{IN} tends to T_{OUT}. Conversely, decreasing θ brings T_{IN} closer to T_S. The unknown heat gain parameter G also influences internal conditions; an increase in G results in increased T_{IN}.

Measurement of T_{IN} provides an indirect measurement of G, which is sufficient for control purposes. Consider a first order expansion of T_{IN} in Equation (4) in terms of θ. Differentiating T_{IN} with respect to θ and approximating $(1+\theta)^{-1} by$ $(1-\theta)$ yields:

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

$$\begin{aligned}\frac{\partial T_{IN}}{\partial \theta} &= \frac{T_{OUT}}{1+\theta} - \frac{(T_S + \theta T_{OUT} + G/hA_S)}{(1+\theta)^2} \\ &= \frac{(T_{OUT} - T_S - G/hA_S)}{(1+\theta)^2}.\end{aligned} \tag{5}$$

Solving Equation (4) for $G/(hA_S)$ yields:

$$\frac{G}{hA_S} = T_{IN} - T_S + \theta(T_{IN} - T_{OUT}), \tag{6}$$

Substituting Equation (6) in Equation (5) and simplifying yields:

$$T_{INf} = T_{INi} + \Delta\theta \frac{T_{OUT} - T_{IN}}{1+\theta}, \tag{7}$$

Here, T_{INf} is the final internal temperature after an adjustment in θ of magnitude $\Delta\theta$. T_{INi} is the initial internal temperature. Equation (7) is an approximate analytical expression for the internal temperature after a control action. It shows that changes in T_{IN} resulting from a given change in θ have the same sign as, and are linearly dependent on, $T_{OUT} - T_{IN}$. On the basis of this analysis, warm-weather control rules were established as given in Table 4.

4.3 Windward cold, leeward warm

As a result of solar gains on the SE façade of the building, the leeward side is often warm when the windward side is cold in the early morning on 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 on the leeward side, the ventilation mode number is increased by one. In order not to increase the cooling needs of the leeward users, but still address the need for heating on the windward side, the windward heating set-point is set to 18°C.

4.4 Windward warm, leeward cold

This case is the opposite of the previous case, but is not as problematic because the windward side users can address their needs by adjusting their operable windows without significantly changing the overall flow rate (see Figure 4). For these reasons, in this situation, the control system will reduce the mode number by one and set the leeward heating set-point to a relatively high value (21°C) to ensure heating on this side.

4.5 Night cooling

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

In the future, the design team intends to incorporate weather prediction information in the control system, basing the decision to night cool on the predicted weather for the next day in addition to possible heat accumulation in the space during the previous day.

5 Simulation of system performance

In order to test and develop the low energy cooling system and its BMS control strategies, the building and user behaviour where modeled using EnergyPlus with the COMIS[3] natural airflow model. The model implemented to test the initial design principles[1] was used in the simulations presented below (including internal heat gains and building occupation schedule). This model has four zones: the two occupied 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 naturally ventilated portion of the building starts at the sixth floor, and adjacent buildings do not exceed this height, so all the naturally ventilated floors are exposed to the wind. The simulation used pressure coefficients measured in a boundary layer wind tunnel. Pressure coefficients representative of average wind pressure exposure in the naturally ventilated portion of the building were chosen.

The modularity of EnergyPlus allowed for the inclusion of a custom control subroutine that was used to simulate and tune the operation of the BMS system. The transmissivity of the metal shading scrim in 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 were used (TMY, airport data).

6 Results

We begin by considering performance of the building controlled solely by the BMS, which is Case 1 in Table 5. Our analysis of the two mean weather years showed that the critical times for cooling consist of sequences of no more than three hot summer days. At other times, the temperate climate presents no real problems for the control of the indoor environment. First we consider the behaviour during a sequence of warm summer days and then we address the performance over the entire year.

Table 5 The five cases tested. Informed users(IU), uninformed users(UU) or no opening of the user operated windows are indicated in the last column

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

6.1 Warm summer days

Figure 5 shows the predicted temperatures in the NW and SE bays and in the surface of concrete ceiling slab, over a sequence of hot days in July. The simulation time step is 10 minutes and the control algorithm updates the ventilation mode number every step time. The results are plotted as 30-min averages. The first day shows typical behaviour on a mild day when the external temperature stays below 20°C. As can be seen from Figure 5, between 10 am and 2 pm the BMS system is in MDN 8, showing that cool outside air is removing internal heat gains. The interior temperatures remain comfortable throughout the day.

The second day is a typical warm day in which the external temperature reaches almost 30°C. The BMS system selects the minimum daytime mild/warm mode (MDN 5) to optimize the cooling produced by the ceiling slab. The air temperatures in the bays exhibit two different behaviours during the day. During the morning TaSE > TaNW, as a result of solar gains in the SE façade. For wind from the NW, the air stream is attached to the ceiling slab until it enters the SE bay and in the afternoon TaSE < TaNW, as a result of the cooling of the air stream by the slab. The maximum internal temperature is less than 26°C.

Similar system behaviour occurs on the following two warm days. During the unoccupied night time periods, the system promotes night cooling by selecting the maximum opening mode (MDN 10). Figure 5 shows that the slab temperature increases over this period and the effectiveness of the night cooling diminishes with time.

The third day clearly illustrates the performance of the control system; even with an outside temperature of more than 34°C the inside temperature is below 29°C. On the fourth day, the interior temperature is almost the same as on the previous day, although the peak external temperature has decreased from 35°C to 30°C. However, our analysis of the weather data shows that occurrences of 4 or more consecutive days with maximum temperatures above 30°C are very rare.

Figure 6 shows the average dry resultant temperature in the two bays for the same days as shown in Figure 5. (The dry result temperature is the mean of the air temperature and the radiant temperature and is a reasonable proxy for thermal comfort.) The dry resultant temperature shows the same trend as the indoor air temperature, but is 1–2F lower. As expected, air flows from NW to SE for most of the time during these summer days. However,

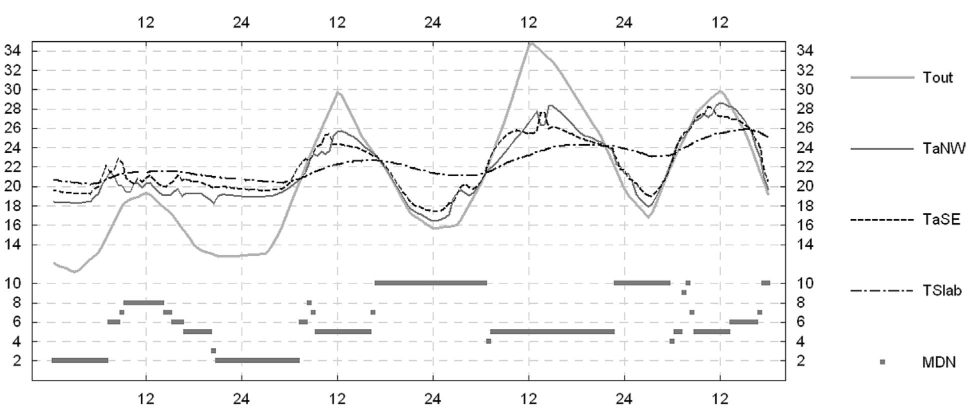

Figure 5 Predicted temperatures for case 1 in a sequence of warm days in July. All temperatures in °C. T_{out}: outside air temperature. T_aNW: average air temperature in the North West bay. T_aSE: average air temperature in the South East bay. T_{Slab}: average surface temperature of the concrete ceiling slab. MDN: BMS system window opening mode

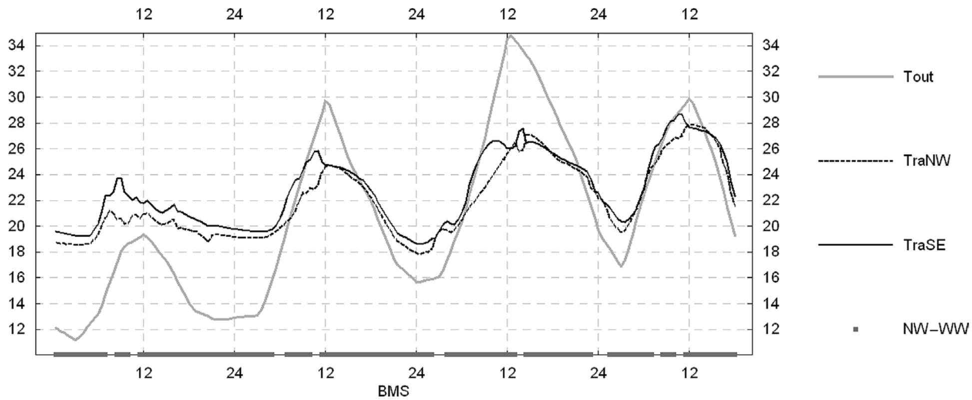

Figure 6 Predicted comfort temperature and airflow direction for a sequence of warm days (case 1). All temperatures in °C. The two bay temperatures shown (Tra-NW, SE) are obtained by calculating the average between the average air and mean radiation temperature in each zone. The grey squares labeled NW–WW signal cross-ventilation airflow entering the building in the NW bay and exiting in the SE bay

there are occasional changes in wind direction, such as the one visible at 1pm on the third day. As a result of this wind direction change, the dry resultant temperature in the SE bay increases as the airstream cooled by the slab is replaced by a stream of warmer outside air.

To illustrate the opposite extreme, Figure 7 shows the behaviour over the same days, but with no BMS and 'uninformed' user behaviour (Case 5 in Table 5). The grey squares labeled MDN indicate the fraction of user operable windows that are opened at a given time, varying between 0 (closed) and 10 (fully opened). In this case, the internal temperatures track the external temperature closely, peaking at about 34°C on the hottest day. Comparison

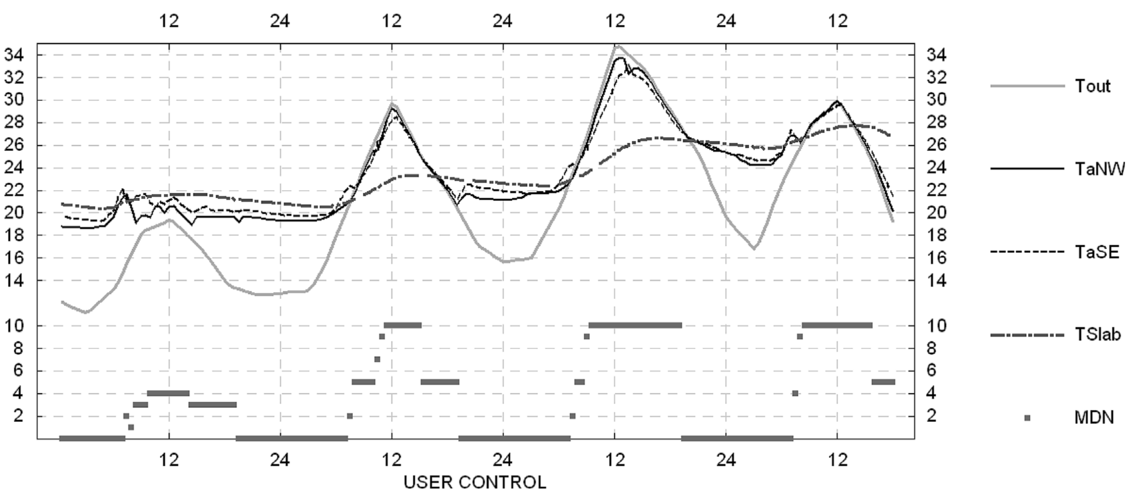

Figure 7 Indoor temperatures for a building with no BMS and uninformed users (case 5). In this chart, MDN is the user operable opening level, from closed (0) to fully open (10).

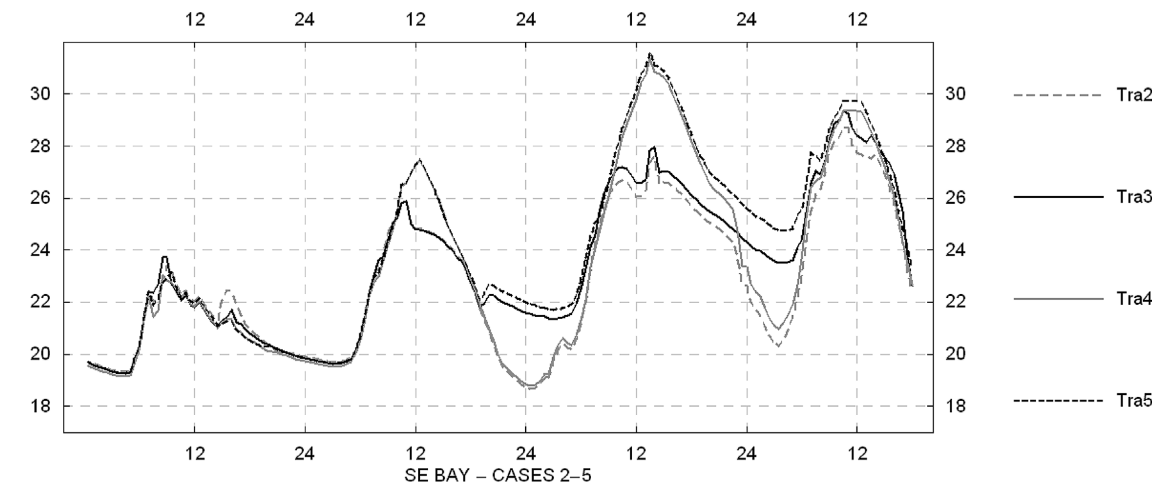

Figure 8 Temperatures in the two building bays for Cases 2–5

with Figure 5 shows that the BMS achieves a reduction of about 6 K over this worst case. This is a significant reduction, which is sufficient to provide comfortable internal conditions throughout the year.

Figure 8 shows a comparison of the predictions of comfort temperatures for four intermediate control strategies, Cases 2–5. It is clear that uninformed users can have a significant negative impact in indoor climate conditions, with much larger diurnal temperature changes for Cases 4 and 5 compared to Cases 2 and 3, which either have no user action or informed user action. According to our assumptions, uninformed users make limited use of the cooled slab, resulting in higher indoor temperatures. Since the area of user-operable openings is comparable to the BMS controlled area, this impact extends to Case 4. The absence of night cooling results in a 1 K increase in the temperature on the warmest days.

6.2 Annual performance

Calculations for the two mean weather years were analyzed to determine the times when the building is uncomfortable. The heating system is adequately sized and we restrict our attention to the times when the internal temperature is high. EnergyPlus simulations were performed for the five cases in Table 5, and the number of hours in the expected operation schedule of the building (taken to be 0800–1800) that exceeded a given temperature was calculated. The results are given in Table 6.

The number of hours above 26°C is small, independent of the user behaviour. Even for the worst case (Case 5) a maximum of 4.2% of the daytime hours have temperatures above this value. This corresponds to 15 days. For the best case (Case 2) this is reduced by a factor of 2, to 7 days. If the threshold is set to 28°C, the best case has warmer temperatures for 2.3 days.

Table 6 also shows that the SE bay has higher temperatures than the NW bay. These temperatures are found to occur in the morning as a result of solar gains through the façade. In order to reduce this gain a metal scrim will be erected along the SE façade, as shown in Figure 1.

The effects of varying the solar and optical transmissivity of the SE metal scrim between 30 and 60% for Cases 2 and 5 are shown in Figures 9 and 10.

Table 7 shows an additional indicator of thermal stress obtained by summing, for each hour with temperature above a given value (24, 26 and 28°C as in Table 6) the number of

Table 6 Percentage of hours during daytime operation schedule that are above 24, 26, 28 and 30°C

Case	Hours > 24°C		Hours > 26°C		Hours > 28°C		Hours > 30°C	
	NW	SE	NW	SE	NW	SE	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

degrees that the inside temperature exceeds the threshold:

$$\sum_{\text{hourswithT62;}T_T} (T - T_T) \tag{8}$$

where T is the temperature in each bay during occupied hours and TT is the threshold used to obtain each column in Table 7. In order to improve readability, the values in Table 7 from the Equation (8), for the 2 years simulated, are divided by 1000.

The results obtained are very similar to Table 6, still, this indicator shows higher sensitivity, allowing better distinction between cases 1, 3 and 5. For example, the first column of Table 7 shows an increase in thermal stress of 151% between cases 1 and 5, up from 91% in Table 6.

Figure 9 shows the effects on warm days. Doubling the scrim transmissivity increases the temperature by about 2 K. The effect is most pronounced before noon, but there is a noticeable effect throughout the day. Figure 10 illustrates the typical effect on winter days. As a result of the SE façade orientation, the solar gains are significant in winter and result in excessively high air temperatures, especially in the case with 60% scrim transmissivity. Figure 10 shows that the BMS tries to reduce overheating in the SE bay by increasing the selected window opening mode and, consequently, the airflow rate (by selecting MDN $\geq$ 6), and decreasing the heating set point in the NW bay. Table 8 shows the effects of doubling the scrim transmissivity. The discomfort, as indicated by the number of hours

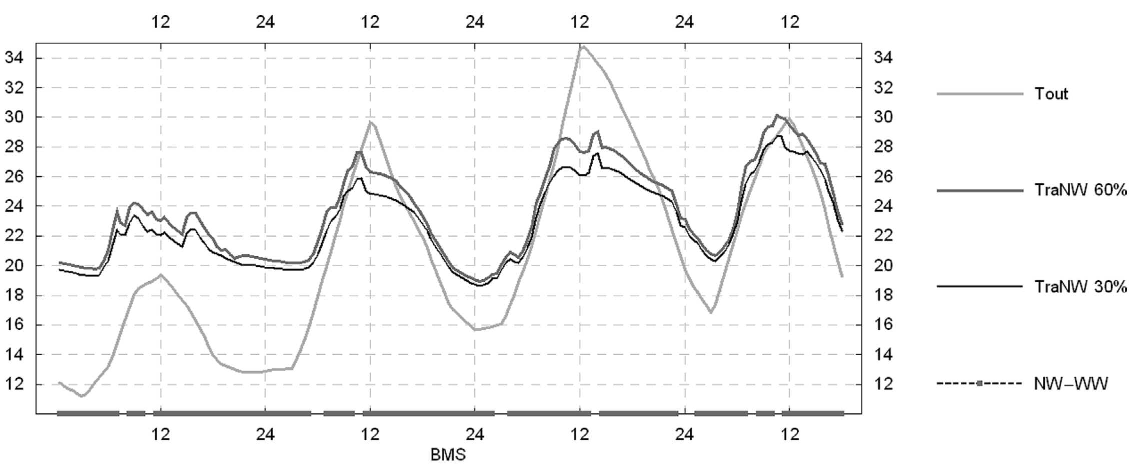

Figure 9 Effects of scrim transmissivity on the comfort temperature in the SE bay for a sequence of warm days in July

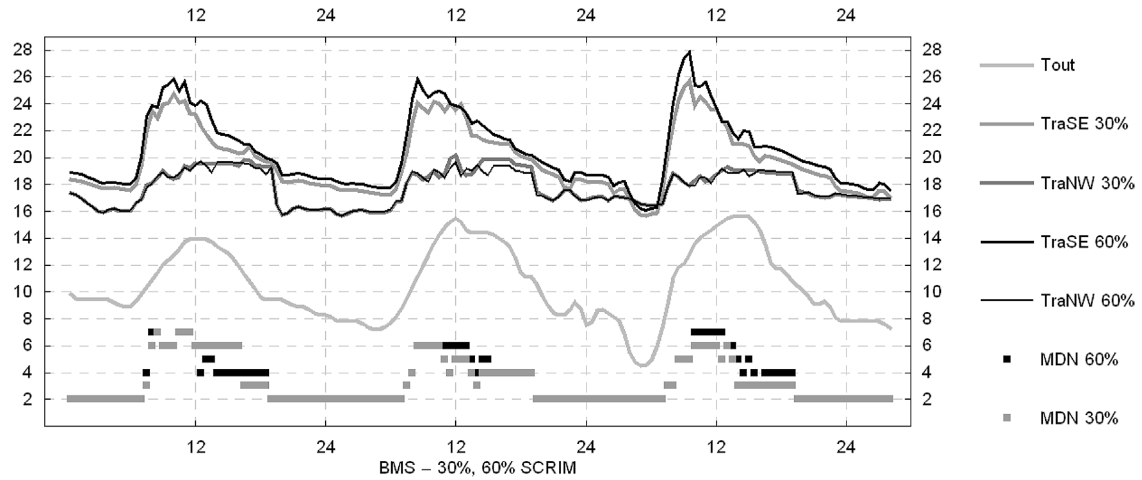

Figure 10 Effects of scrim transmissivity on the temperature in both bays during cold days

above 24–28°C increases by ~100% in the SE bay (compare with Table 6).

Figure 11 is a graphical representation of the results shown in Table 6. It shows the percentage of hours in excess of the threshold temperature for each of the five cases in Table 5. Night cooling (Cases 1, 2 and 4) has a significant impact in indoor climate conditions, giving significantly cooler conditions. It is particularly effective in reducing peak temperatures between 24°C and 26°C.

Operation of the BMS system always results in improved indoor climate conditions, even when users behave in an uninformed way (Cases 4 and 5). In San Francisco's mild windy climate, informed user behaviour (Cases 2 and 4) is essential only in the warmer hours. Because days with warm hours ($T_{OUT} >$ 25°C) are infrequent (on average, 20 days per year) the impact of incorrect user behaviour is not as significant as might be expected from a simple analysis of the results in Figures 7 and 8.

7 Conclusions

This paper describes the development of a control strategy for the window openings on the naturally ventilated floors of the proposed San Francisco Federal Building. The proposed control strategy is tested by simulating the building with EnergyPlus.

Table 7 Estimation of discomfort due to excessive heat, for indoor temperatures above 24, 26, 28 and 30°C

Case	H. T > 24°C		H. T > 26°C		H. T > 28°C		H. T > 30°C	
	NW	SE	NW	SE	NW	SE	NW	SE
1	21.4	111.7	4.7	22.5	0.3	6.3	0.0	1.6
2	23.7	99.8	6.2	21.4	0.8	6.3	0.0	1.5
3	38.2	174.4	8.7	37.7	1.4	10.5	0.0	2.6
4	38.9	98.1	13.7	30.9	4.0	10.9	0.3	2.6
5	53.6	159.5	16.6	45.8	5.0	14.7	0.5	3.8

The values shown in the tables are in Degree-Hour. Discomfort is estimated by adding the hours above the temperatures shown multiplied by the temperature differential.

Table 8 Percentage of hours during daytime operation schedule that are above 24, 26, 28 and 30°C using a scrim with 60% solar/optical transmissivity

Case	Hours > 24°C		Hours > 26°C		Hours > 28°C		Hours > 30°C	
	NW	SE	NW	SE	NW	SE	NW	SE
2	2.2	23.5	0.8	6.7	0.2	1.7	0.0	0.5
5	4.3	29.9	1.5	9.9	0.5	2.9	0.2	1.0

The control strategy uses the results of previous CFD calculations[1] on the wind-driven cross ventilation. This study showed that the air stream attaches to the ceiling and is effective in exchanging heat with the exposed ceiling slab. Window opening is used to control the amount and distribution of the airflow.

This control strategy was tested by simulating 2 years of weather data using EnergyPlus and COMIS.[3] The results show that the mild San Francisco climate produces comfortable interior conditions for most of the year. The main problem is modest overheating during a sequence of warm summer days. Night cooling and optimal use of the chilled slab during the day is an appropriate strategy to deal with the warmest periods. The indoor climate conditions in the SE bay of the building are very sensitive to the transmissivity of the shading scrim.

This building has a significant number of user-controlled openable windows. The simulations show that user behaviour can have a significant impact on the performance of the building. Uninformed users can increase the number of warm hours by almost an order of magnitude over informed users. Since informed user behaviour may be counter-intuitive, such as closing windows to optimize slab cooling on hot days, optimal performance requires that users receive education on the operation of the building. As detailed in the paper, the proposed control strategy should give a comfortable indoor climate for the vast majority of the time. With good user behaviour, it is expected that the inside temperature will exceed 28°C for less than 20 h per year.

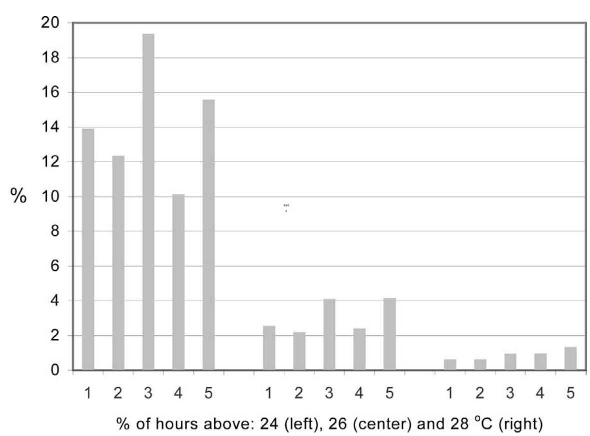

Figure 11 Percentage of hours above 24, 26 and 28°C during office operation hours (8 am–6 pm)

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References

1 Haves P, Linden PF, Carrilho da Graça G. Use of simulation in the design of a large naturally ventilated commercial office building. *Building Serv. Eng. Res. Technol.* 2004; 25: x–x.

2 McConahey E, Haves P, Christ T. The integration of engineering and architecture: a perspective on natural ventilation for the new San Francisco Federal Building. *Proceedings of the 2002 ACEEE Summer Study on Energy Efficiency in Buildings*. Asilomar, CA, August, 2002.

3 Huang J, Winkelmann FC, Buhl WF, Pedersen CO, Fisher D, Liesen R, Taylor R, Strand R, Crawley DB, Lawrie LK. Linking the COMIS Multi-zone Air Flow Model with the EnergyPlus Building Energy Simulation Program. *Proceedings of Building Simulation '99* IBPSA, Kyoto, Japan, 1999.

4 Etheridge DW, Nolan JA. Ventilation measurements at a model scale in a turbulent flow. *Building and Environment* 1979; 14: 53–64.