Title
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Performance, Prediction, and Optimization of Night Ventilation across Different Climates:
An assessment of mechanical and natural night ventilation

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ABSTRACT:

This paper describes the performance, in terms of indoor environmental conditions, of three buildings from both the U.S. and India that use night ventilation as their primary cooling method. The first building, located in Oakland, California, uses forced ventilation at night to increase the airflow. The second building, located in Sunnyvale, California, uses automated natural ventilation at night. The third building, in Auroville, India, uses natural ventilation by means of occupant-controlled windows. The analysis is based on three months, two months, and a full year of monitored data collected from each building, respectively, of indoor and outdoor conditions. The indoor conditions of each building were first tested for compliance with comfort standards in the US and India. A hybrid model was then developed, using both first principle equations and the collected data, to predict the instantaneous air and mass temperatures within each building. The cooling strategy effectiveness was then assessed by comparing indoor conditions from days that did and did not use night ventilation, comparing performance across the different climates and types of night flushing. Finally, the ventilation controls for each building were optimized using the hybrid model.

Keywords: night ventilation, pre-cooling, comfort

INTRODUCTION

Night ventilation, or night flushing, is a passive cooling technique that utilizes the outdoor diurnal temperature swing and the building's thermal mass to pre-cool a building through increased airflow at night, allowing radiant cooling to take place during the day when the building is occupied. Both passive and mechanical night ventilation have the potential to reduce energy consumption in air conditioned buildings (Kolokotroni, 1999). Numerous studies have looked at the parameters that have the strongest effect on the performance of night ventilation, one of which determined that climatic conditions and airflow rate have the largest impact on the efficiency of the strategy (Artmann, 2008). Additionally, many have examined the efficacy of night ventilation through field studies. One study conducted full scale experimentation in three buildings operating under free-floating and mechanically cooled conditions (Geros, 1999). Another study monitored and analyzed the performance of real buildings using different ventilation typologies (Givoni, 1998). A third carried out long-term monitoring of air and surface temperatures inside 12 rooms of an office building (Pfafferott, 2004). Using methods established in previous field studies, this paper looks at the impact of climate and control algorithm on the performance of the night ventilation with regard to the adaptive comfort model, indoor conditions, and heat removed.

BUILDING DESCRIPTIONS

Building 1 is located in Oakland, CA, which has a fairly mild climate. This facility functions as an elementary school and uses forced night ventilation to pre-cool its classrooms. Each classroom contains thermal mass in the form of a 4-inch concrete slab (145 pcf) and 2-inch cement plaster wall finishes (95 pcf). The mechanical system is designed to enter Night Ventilation mode (NV), which consists of ramping up the air flow rate during unoccupied hours (4PM-8AM), when the thermal mass temperature is at least 1°F higher than the mass temperature setpoint and the outdoor air temperature is at least 10°F below the mass temperature. The system will leave NV when the mass temperature falls below the mass temperature setpoint. The system will sometimes enter a "warm-up mode" in the morning if the indoor air temperature is below a specific threshold. The mechanical system is also designed to enter Daytime Cooling mode (DC), which consists of ramping up the air flow rate during occupied hours, when the indoor air temperature exceeds 74°F. When the building is not in either cooling mode, it is in Regular Airflow mode (RA), meaning the space is being ventilated at the minimum allowable airflow rate during occupied hours. Indoor conditions from Building 1, including embedded mass wall temperature, embedded mass floor temperature, indoor air temperature, supply temperature, and airflow rate were collected via the Building Management System (BMS) for 8 classrooms.

Building 2 is located in Sunnyvale, CA, which also has a mild climate. The facility functions as an open-plan office with 12-inch concrete walls and uses automated natural night ventilation to pre-cool the building. The system enters NV by opening up the windows and skylights during unoccupied hours (8PM-6AM), when the indoor air temperature is greater than 70°F and the outdoor air temperature is less than 68°F. The systems leaves NV when the indoor air temperature falls below 69°F. Unlike Building 1, mass temperature is not one of the criteria for the operating algorithm. When Building 2 was not in NV mode, the windows remained closed for the previous night. Indoor conditions from Building 2, including embedded mass wall temperature, indoor air temperature, internal loads, and window state were collected via the BMS for the open plan office.

Building 3 is located in Auroville, India, which has a hot and humid climate. This facility is residential and uses occupant controlled natural night ventilation to pre-cool the house. The building contains thermal mass in the form of compressed earth block walls (290x140x90 mm) and a ceiling/roof construction consisting of 2 cm cement plaster finish and Hurdi terra cotta hollow blocks. The occupants typically open their windows when the outdoor air temperature is equal to the indoor air temperature. When Building 3 was not in NV mode, the windows remained closed for the previous night. Indoor conditions for Building 3, including mass wall surface temperature, indoor air temperature, and window state, were collected via HOBO data loggers in one zone of the building.

METHODS

Nomenclature

T	Temperature [°F OR °C]
R	Thermal resistance [°F-hr/BTU OR °C-hr/J]
C	Thermal capacitance [BTU/°F OR J/°C]
V	Ventilation rate [ft^3/hr OR m^3/sec]
s	Window state [0/1]
ρ	Density [lb/ft^3 OR kg/m^3]
c	Specific heat [BTU/lb-°F OR J/kg-°C]
P	Power [BTU OR J]
r	Solar radiation [BTU OR J]
t	Time [hr]
Subscript	
I	Indoor air
O	Outdoor air
W	Wall
F	Floor
V	Supply

After data was collected from each building, the data was paired with hourly outdoor air temperature data from local weather stations and solar radiation data from TMY3 weather files and consolidated using the Universal Translator. The final set of data from each building is:

Building 1 July 2nd 2015 – Oct 6th 2015
Building 2 Sept 1st 2015 – Oct 31st 2015
Building 3 Oct 22nd 2013 – Oct 14th 2014

Once all data was consolidated, a baseline data analysis was conducted for each building to determine daily and seasonal trends. For the US data, seasons were defined as follows: Spring from March to May, Summer from June to August, Fall from September to November, and Winter from December to February. For the India data, seasons were defined as follows: Pre-Monsoon from March to May, Monsoon from June to September, Post-Monsoon from October to November, and Winter from December to February.

Then, each data set was compared to the adaptive comfort standard (ACS) in ASHRAE 55. Data from Building 3 was also compared to the newly created India Model for Adaptive Comfort (IMAC), developed at the Centre for Advanced Research in Building Science & Energy (CARBSE). For the purposes of this analysis, a homogenous mean radiant temperature has been estimated based on the area weighted surface temperature. For these comparisons, Discomfort Degree Hours (DDH), a combination of the magnitude and duration of the temperature deviation from the ACS or IMAC 80% acceptability comfort limits, has been used as a performance metric.

Hybrid models were generated in Matlab for each building, by means of simplified resistance/capacitance dynamical equations, the gradient descent method and the non-linear least squares method. The models were based on consolidated data sets of different durations for each building (one month, one month, and six months, respectively), depending on availability of data. The dynamical equations for Building 1 (equations 1, 3, and 4) use uncontrollable inputs of outdoor air temperature and solar radiation, controllable inputs of supply temperature and airflow rate, and produce outputs of indoor air temperature and mass temperature. The dynamical equations for Buildings 2 and 3 (equations 2, 3, and 4) use uncontrollable inputs of outdoor air temperature and solar radiation, controllable input of window state, and produce outputs of indoor air temperature and mass temperature. After model generation, the models were validated with another month of data from each respective building.

$$C_I\dot{T}_I(t) = \frac{1}{R_{OI}}[T_O(t) - T_I(t)] + \frac{1}{R_{WI}}[T_W(t) - T_I(t)] + \frac{1}{R_{FI}}[T_F(t) - T_I(t)] + \rho c V(t)[T_V(t) - T_I(t)] + P_{r,I}r(t) \quad (1)$$

$$C_I\dot{T}_I(t) = \frac{1}{R_{OI}}[T_O(t) - T_I(t)] + \frac{1}{R_{WI}}[T_W(t) - T_I(t)] + \frac{1}{R_{FI}}[T_F(t) - T_I(t)] + P_s s(t) + P_{r,I}r(t) \quad (2)$$

$$C_W\dot{T}_W(t) = \frac{1}{R_{OW}}[T_O(t) - T_W(t)] + \frac{1}{R_{WI}}[T_I(t) - T_W(t)] + P_{r,W}r(t) \quad (3)$$

$$C_F\dot{T}_F(t) = \frac{1}{R_{FI}}[T_I(t) - T_F(t)] + P_{r,F}r(t) \quad (4)$$

Subsequently, the hybrid model was used to determine behaviour of indoor conditions with and without night ventilation. To understand how each building would have performed without night ventilation, a simulation was run for each building without the presence of night ventilation. For Building 1, this meant running a model with inputs in RA mode and DC mode. For Buildings 2 and 3, this meant running a model with windows closed. To assess performance in each ventilation mode, a comparison was conducted between the simulation with real inputs and with non-NV inputs. For this comparison, daily maximum indoor air temperature ($T_{I,max}$), daily maximum damping ($Damp_{max}$, see equation 5), daily time lag ($\boldsymbol{\varphi}$, see equation 6), daily heat removed (Q, see equation 7), and daily DDH were used as performance metrics. A p-value < .05 was considered satisfactory for all t-tests. Remembering that the goal of night ventilation is to reduce the indoor temperature peak, while maximizing the thermal dampening, lag effects, and heat removed, one strategy was considered to perform better than another if:

- Average $T_{I,max}$ was lower
- Average DDH was lower
- Average $Damp_{max}$ was higher
- Average $\boldsymbol{\varphi}$ was higher
- Average Q was higher

For the purpose of this analysis, the night ventilation effect is defined in terms of the indoor conditions the day after night ventilation (as described in the building description section) is executed.

$$\boldsymbol{Damp_{max} = T_{O,max} - T_{I,max}} \quad (5)$$

$$\varphi = t(T_{O,max}) - t(T_{I,max}) \quad (6)$$

$$Q = \int_{t_1}^{t_N} V\,\rho_{air}c_{air}(T_I(t) - T_O(t))dt \quad (7)$$

Finally, the ventilation controls for each building were optimized to minimize the time outsize of the ACS 80% acceptability limits. The optimization for Building 1 also aimed to minimize the energy consumed for running fans. This optimization was constrained to follow the dynamics captured in the hybrid models. Additionally, for Building 1, the ventilation rate was constrained by the system capacity and hours of occupancy and for Buildings 2 and 3, the window state was constrained to ensure that the windows were opened and closed at most once per day. After the optimization was run, the previously described performances metrics were compared for models runs with optimized inputs, real inputs, and non-NV inputs.

RESULTS

Baseline Analysis Results

The baseline data analysis of Building 1 showed that the night ventilation scheme is impacting the indoor conditions of the space as anticipated. A typical occurrence of NV can be seen in figure 1. On September 10th and 11th, 2015 the airflow in Room 5 ramped up to between 1100 and 1600 CFM and the supply temperature dropped to approximately 65°F between the hours of 12AM and 6AM. Although the outdoor air temperature went as high as 85°F the following day, the indoor air temperature peaked at 76.5°F and the mass temperature peaked at 75.5°F with a 2 hour and 7 hour time lag, respectively.

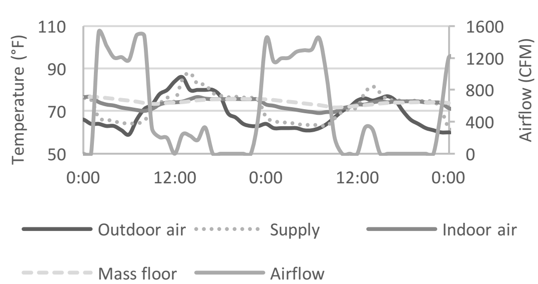

Figure 1: NV in Building 1 Room 5: 9/10/15 - 9/12/15

The baseline data analysis of Building 2 indicated that the NV strategy has very little impact on the indoor conditions. As seen in figure 2, on September 18th, 2015 the windows automatically opened at 11:30PM and closed at 6AM when the indoor air temperature reached 69°F. The following day the outdoor air temperature peaked at 2:30PM at 82°F, while the indoor air temperature peaked 6 hours later at 74°F, clearly showing the thermal lag effect of the mass. It should be noted that the mass temperature was unaffected by the NV strategy on this day and remained constant at 69°F.

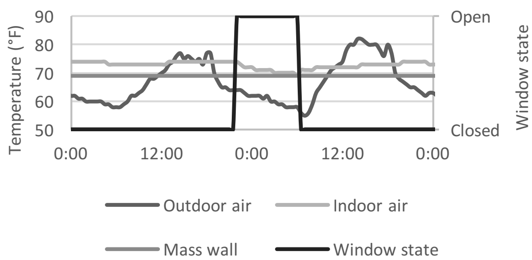

Figure 2: NV in Building 2: 9/17/15 - 9/19/15

In Building 3, where the occupants are manually operating the windows, the NV strategy was used almost every day for an entire year. As seen in figure 3, on May 23rd, 2014 the windows were opened by the building occupants at 6PM and closed at 5AM when the indoor air temperature was equal to the outdoor air temperature. The following day the outdoor air temperature peaked at 1PM at 39°C, but the mass effectively delayed and dampened the peaks of the indoor air temperature (5 hours later at 31°C) and the mass temperature (6 hours later at 32.5°C.

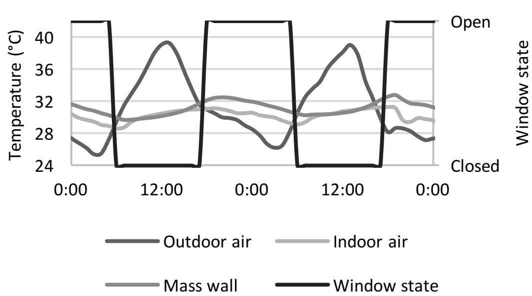

Figure 4: NV in Building 3: 5/22/14 - 5/24/14

Comfort Standard Results

In analyzing the 2-3 months of data from each classroom of Building 1, it was discovered that the operative temperature never exceeded the upper ACS comfort limit. However, the operative temperature tended to hover around the lower ACS comfort limit for almost the entire data set, and in some instances even go below the limit, indicating that the space is being overcooled and therefore wasting energy. Each classroom has at least a few days in which the daily DDH (with respect to the lower comfort limit) exceeds 0 (approximately 19% of data). The average daily DDH across all 8 classrooms is 0.82 °F-h. In some instances, the daily DDH reached as high as 24 °F-h.

For Building 2, the entirety of the daytime hours (756 hours) fell within the ACS 80% comfort limits. This suggests that the night ventilation strategy was successful in maintaining a comfortable temperature. That being said, the operative temperature seemed to stay very close the lower ACS comfort limit, indicating that there is little need for additional cooling.

In analyzing the full year of data from Building 3 with respect to IMAC, it was discovered that the operative temperature never exceeded the upper IMAC comfort limit or fell below the lower IMAC limit. However, when comparing the data to the ACS comfort limits, it was found that the operative temperature exceeded upper ACS comfort limit for approximately 12% of the year, during the Pre-Monsoon and Monsoon seasons, as seen in figure 5. There is a wide spread of operative temperature across the year, but the operative temperature remains closer to the upper comfort limits for a higher proportion of the year. The average daily DDH across the year is approximately 0.38 °C-h. The daily DDH (with respect to the upper ACS comfort limit) exceeds 0 for 42% of the Pre-Monsoon season and 37% of the Monsoon season. During the Pre-Monsoon season, the average daily DDH is 0.58 °C-h and goes as high as 6 °C-h. During the Monsoon season, the average daily DDH is 0.68 °C-h and goes as high as 9.5 °C-h. The total DDH for the entire year is 131.7 °C-h.

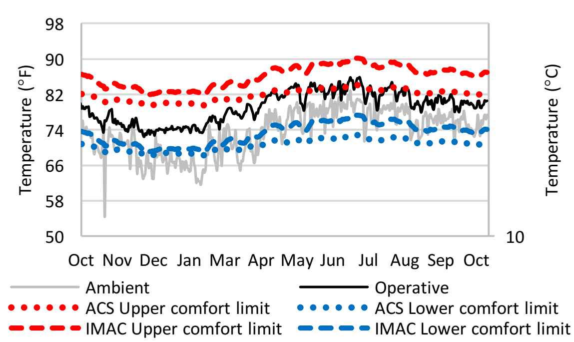

Figure 5. Building 3 operative temperature with comfort limits

Model Results

After completing a comfort analysis of each building, hybrid models were generated for each building as discussed in the methodology section. The mean absolute percent error and standard deviations are seen in table 1. For the most accurate model (Building 1 Room 2), 95% of the temperature predictions match the actual temperature within 1.5°F. For the least accurate model (Building 3), 95% of the temperature predictions match the actual temperature with 1.6°C. The simulated and real mass temperature for Building 1 Room 1 can be seen in figures 6. These errors were considered small enough to use the models as representative of actual behaviour.

Table 1: Mean absolute percent error (MAPE) and standard deviation (SDAPE) in hybrid models

Building	Room	MAPE (%)	SDAPE (%)
1	1	1.5	1.6
1	2	0.65	0.80
1	3	0.80	0.70
1	4	0.89	0.90
1	5	0.91	0.88
1	6	1.2	1.3
1	7	1.3	1.1
1	8	1.5	1.3
2	-	1.9	1.4
3	-	2.3	1.8

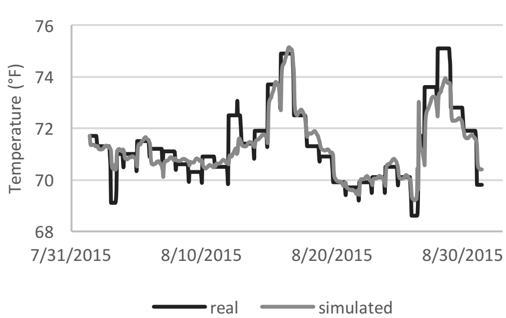

Figure 6. Real and simulated mass wall temperature in Building 1 Room 1: 7/31/15-8/30/15

For Building 1, no statistically significant differences were seen between model simulations with different ventilation inputs with regard to $T_{I,max}$, $Damp_{max}$, φ, or DDH. This indicates that the airflow rate has very small influence on the indoor conditions, which are much more closely correlated to the supply temperature. The only metrics to have a statistically significant difference between models with different ventilation inputs was Q. All of the models with simulated ventilation inputs removed less heat than the model with real inputs. The simulated ventilation models are probably removing less heat because the real building is going into night ventilation or daytime cooling more often than the design control sequence calls for, which calls into question how the control sequence has changed since operation began.

For Building 2, no statistically significant differences were seen between model simulations with and without night ventilation. This indicates that the strategy was not impacting the internal conditions. In both the model analysis and baseline analysis, mass temperature was not affected by the NV strategy. That being said, the mass temperature has almost no fluctuation and does not appear to be influenced by the outdoor air temperature, possibly because the climate of Sunnyvale is so moderate and the mass is so heavy.

For Building 3, statistically significant differences were seen between model runs with and without night ventilation with regard to $T_{I,max}$, $Damp_{max}$, and DDH. During the warmest seasons of the year (Pre-Monsoon and Monsoon) when NV was utilized, $T_{I,max}$ and $Damp_{max}$ improved by about 0.7°C on average and DDH improved by 3.5 °C-h on average (figure 7). Although this difference is not that large, the NV strategy is still somewhat alleviating the indoor conditions and can significantly improve comfort when paired with other strategies, such as ceiling fans. Surprisingly, no statistically significant differences were seen between ventilation modes with regard to φ.

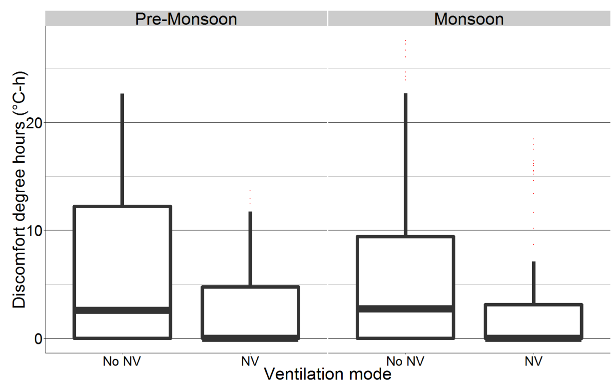

Figure 7. Building 3 DDH with & without night ventilation

Optimization

After running the optimization on all classrooms in Building 1, the system operated with only minimum allowable airflow. This suggests that these classrooms need no night ventilation to satisfy comfort requirements.

For Building 2, because the identified parameter associated with window state was so small, there was minimal impact on the indoor conditions from night ventilation. Therefore, the controls for night ventilation in this facility were not optimized.

For Building 3, the window state was optimized for one of the hottest weeks of the year (figure 8). A statistically significant difference was seen between the optimized model and the other two models with regard to $T_{I,max}$, $Damp_{max}$, and DDH. Although the optimized model only performed 0.8 °C better than the model with real window state, it nearly doubled the reduction in temperature compared to the case with no night ventilation. The discomfort degree hours were reduced by approximately

56% after incorporating night ventilation, and a further 34% by optimizing the controls. This suggests that if the building were to use model predictive control in determining when to open the windows, they could seriously improve the comfort inside the space.

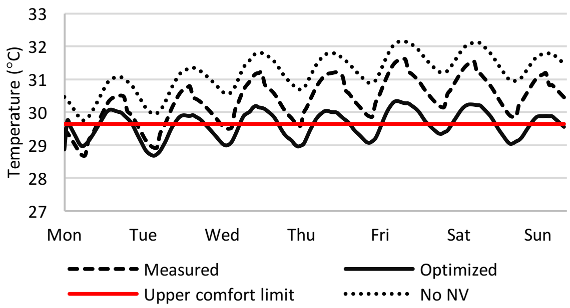

Figure 8. Building 3 measured, optimized, & no NV operative temperature

DISCUSSION

Results indicate that the night ventilation strategy is performing at varying degrees for each building. Because each building is so different in its typology (location, material, and program) and functionality (ventilation system and control), it is difficult to predict exactly what causes the strategy to perform well or poorly in each case.

The results of this study suggest that the NV strategy, in combination with the physical construction of the building, is successfully keeping Building 1 classrooms below the maximum comfort limit during hot periods. However, the strategy is sometimes overcooling the classrooms, which raises the need for passive cooling in this space. Because night ventilation is bringing the indoor temperature too low during night-time periods, the system is actually using more energy in the morning to warm up the space before occupancy. Overcooling is probably taking place because the mass temperature setpoint for entering night ventilation is simply too low. Another potential explanation is that the necessary difference of 10°F between mass temperature and outdoor air temperature for entering night ventilation is too high, especially because this occurs so often in the mild climate. It is very telling that when the controls were optimized to minimize time outside of the comfort bounds, the system never entered night ventilation mode.

The study also suggest that the NV strategy, in combination with the physical construction of Building 2, has no discernible impact on the internal conditions of the space. The most likely reason for the low impact of night ventilation is the extremely high level of thermal mass and low internal loads. The very thick concrete walls and floor are likely able to take care of the load all on their own. It is entirely possible that the night ventilation strategy would have a larger impact if the mass was less heavy or if the internal loads were higher. Additionally, the strategy never ran for more than a few days at a time. Because the mass is so heavy, the strategy might have shown a higher effect on internal conditions if run for many days in a row.

Finally, the study indicates that the NV strategy, in combination with the physical construction of Building 3, successfully lowers the indoor temperature, removes heat from the space, and reduces discomfort degree hours, especially during the hottest seasons of the year. This is very significant because the strategy implemented in this building is very simple and the night ventilation is not always believed to work successfully in hot and humid climates. This being said, the effect size of damping the indoor temperature due to night ventilation is fairly small. Although small differences in temperature can make a larger difference in climates with high humidity, the strategy probably cannot achieve enough on its own to take care of the entire load. Night ventilation, paired with other low energy strategies, such as ceiling fans, has the potential to maintain comfort in this climate. The annual discomfort degree hours for Building 3 was approximately 131.7 °C-h. If the air speed were increased to 0.6 m/s through the use of ceiling fans, the annual discomfort degree hours drops to 2.6 °C-h, and 0 °C-h at air speeds above 0.6 m/s.

There are numerous limitations to this study, most of which are attributed to the limited availability of data. Firstly, many parameters critical to the model calculations conducted in this study were not available and therefore had to be estimated. Another major limitation to the study is the simplicity of the model generated for comparison. Although this model achieved very small errors compared to measured data, the model still utilizes very simplified dynamical equations, and therefore cannot truly capture the dynamics of the heat in the space. The final limitation to this study is the lack of a control case. In terms of the performance within each individual buildings, there was no control period in which night ventilation was not used.

CONCLUSION

The performance of pre-cooling through night ventilation was assessed in three buildings located in the United States and India, and a hybrid model was successfully developed for each building. Building 1, which is located in a mild climate and uses mechanical night ventilation with criteria based on mass temperature, saw little impact from night ventilation and seemed to be overcooling the building. Building 2, which is also located in a mild climate and uses automated natural night ventilation with criteria based on air temperature, satisfied the ACS comfort standard, but also saw very little impact from nigh ventilation, probably due to the heavy mass. Building 3, which is located in a hot and humid climate and uses occupant-driven natural night ventilation, performed well in night ventilation mode, especially in the Pre-Monsoon and Monsoon seasons, and saw even further improvement from optimization.

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