Occupant-Centered Building Operation Strategies for Balancing Thermal Comfort and Energy Efficiency in Warm and Humid Climates

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Abstract
Through detailed monitoring and analysis of how occupants use energy in buildings, insight into energy efficient operation and control methods can be developed alongside human comfort indicators. Maintaining human thermal and visual comfort in passively ventilated and conditioned homes is a multi-sensory experience and requires a dynamic interaction between the occupant and the building. Five 60-hour operation experiments were carried out by the research team in a community design research lab during the Midwest summer of the United States. The goal of these experiments was to keep the buildings operational temperature within the adaptive comfort zone provided by ASHRAE 55 (ASHRAE, 2013) and thus minimize the need for active system use. The researchers kept a detailed operation log recording the time stamps of different operations in the lab. A trained energy simulation model is used to predict cooling energy consumption without these operations. Comparing to measurement in the house, the energy impact of different operations are quantified as an additional indicator. In conclusion this paper presents a series of experimentally validated operational control strategies for a hybrid designed lab located in a climate with warm and humid summers. Weather dependent operation strategies and their energy efficiency are provided to enhance the relationship between people and buildings. This approach leads to more energy efficient behaviours as well as more responsive systems of control.

Keywords: occupants behaviour, building operation, passive strategy, energy saving.

1 Lab Context and Components
The Iowa NSF EPSCoR community design research lab is located in Iowa, USA and occupied all year round by staff, who operate and maintain the building as a nature activity center. The building’s mechanical systems and enclosure must be able to mitigate the harsh cold winters as well as hot and humid summers associated with the ASHRAE Climate Zone 5. The hybrid lab is designed to not only weather those extremes but capitalizes on solar energy and passive ventilation opportunities that produce and conserve energy. Converting solar radiation into usable energy through the use of a photovoltaic array as well as a sunspace, which captures radiation in the form of heat to offset active heating system costs within the lab, are just a few ways in which this building utilizes its renewable energy resources.

The lab (Figure 1) has a series of operable components which allow for flexibility through the seasons. Lower windows near work spaces allow for cross ventilation through the
corresponding upper clerestories during passive ventilation opportunities. The lab’s shed roof stratifies the convective air flows in the space, separating rising heat from the occupants and inducing air flow through the space when both the inlets and outlets are open during warm weather seasons. Exterior sliding louvers located over the southern and eastern windows allow for solar heat gain mitigation through those surfaces with the option of withdrawing them completely during overcast days.

The operable louvers control light levels in the space alongside reducing cooling loads during high temperature days with strong solar radiation. The lab’s sunspace provides passive heating opportunities during cold seasons but must be flushed out during hot summer days. This is done through closing all interior sunspace components and opening the exterior doors to allow for heat to escape. The solar collector loop on the roof works adjacent to the photovoltaic system in harvesting the sun’s thermal energy for use within the lab. The loop utilizes readily available solar energy for use in the lab’s radiant floor heating system and offsets energy costs normally generated through electrical, natural gas, water, or forced air heating systems.

A Data Acquisition System (DAS) has been monitoring the indoor and outdoor environment, mechanical and electrical system for over 4 years. A data driven HVAC system control is fed by real time measurements. Recently a dashboard displaying the key data needed for operation and the website terminal of HVAC system control was launched in the house to better visualize the house performance and ease the occupants’ control decisions. The lab’s combination of sensors used to measure interior and exterior variables are distributed evenly throughout the interior of the house as well as located within the weather station on the roof. Supplying a constant stream of data to the lab’s data acquisition unit provides direct feedback to the occupants as well as historical reference for future performance monitoring.
2 Research Question
The house had originally been designed as a residence. After the house being transformed into an office for naturalist and visitor center of Honey Creek Resort State Park in Iowa, the occupants’ interaction with the house changed from the original design intention. In spite of the flexibility of operating the house with multiple passive strategies, the house operations often relied more on active HVAC system control for the majority of the time. In addition due to some maintenance issues of the building envelope and security concerns, the stack and cross ventilation and sunspace operations were difficult to operate during a daily routine and thus were abandoned by the house occupants. These altered usages of the house could reverse the energy saving of passive operation to increased energy consumption (He, et al, 2014). To develop an ideal house performance as designed, a researcher was operating the house for five time periods during the summer of 2015.

3 Research Method
During a series of five controlled experiments a researcher occupied the lab for a period of 60 hours to monitor and operate the buildings components. Monitoring of interior and exterior environmental variables as well as climatic conditions allowed for informed manipulation of the building’s envelope to capitalize on passive ventilation opportunities and reduce solar heat gain. A series of factors were monitored in relation to the internal and external environments through a building data visualization interface which communicates real time data to the occupant. This information facilitates informed decision making at any current point in time based on real time data of interior conditions as well as forecasted weather information. The factors monitored during the experiments were as follows:

- Dry Bulb Air Temperature (Interior/Exterior)
- Relative Humidity (Interior/Exterior)
- Wind Speed / Direction (Exterior)
- Solar Orientation / Radiation (Exterior)
- Local Weather Conditions (Exterior)

Outdoor Air temperature, relative humidity, and wind speed play key roles in creating interior conditions which accommodate human comfort during passive ventilation opportunities. Temperature is often the only variable used in determining comfort for interior conditions, occupants often view temperature as how the AC and comfort are controlled in spaces. Adding more variables, including outdoor relative humidity, wind speed and solar radiation levels can help the researcher to make a better informed decision of predicting passive ventilation opportunities.

The ability to predict passive ventilation opportunities as well as the interior conditions they produce can help to reduce active system use and in turn produce energy saving alternatives. During the experiment time frames these five factors were monitored and logged hourly in an excel log to be referenced alongside the data points collected from the lab’s sensors. These processes allow the researcher to monitor the environmental conditions before and after changes are made to the adjustable envelope components.
Operation of the building components can be broken down into a series of tasks completed at different times throughout the day in correlation with solar orientation and weather conditions. During passive ventilation, windows are opened to induce air flow through the space. During unfavourable conditions the windows are closed and the air conditioning unit is used to supplement the space’s interior conditions. The building’s operable components are as follows:

- Opening the lower south windows
- Opening lower east window
- Opening clerestory windows
- Louvers on south windows
- Louvers on east window
- Sunspace Open

During the experiment time frame operations were completed in accordance with three factors: mitigate solar radiation, respond to weather conditions, and facilitate passive ventilation. Following the sun’s orientation across the sky the lab’s louvers were used when direct heat gain could be mitigated to reduce the building’s cooling load by sliding the louvers over the windows and reflecting radiation back out into the environment. Weather conditions were constantly changing and as a response operations were completed throughout the day in order to prevent water infiltration or excessive cooling from storm fronts. During rain events the lab’s openings were all closed disallowing passive ventilation and preventing the introduction of humidity into the space. The lab’s lower and upper windows were opened during comfortable conditions to facilitate passive ventilation as a means of reducing energy use by the lab’s active systems.

A detailed log was used to record operations completed throughout the day as well as the resulting interior conditions of the space. Alongside this data, local weather and the number of occupants was also recorded. This record was then used to correlate the operation logs with the resultant energy loads on the building’s mechanical systems to provide insight into the energy saved during passive ventilation.

Local weather conditions played an important role in implementing operation strategies given that during rain events passive ventilation is only possible if water does not infiltrate the envelope. In order to ensure the safety of the equipment and enclosure passive ventilation was not utilized during major rain events or other inclement weather. The log in Table 1 shows how the exterior weather conditions were recorded alongside environmental variables and a timestamp.
Data from the experiments show that opportunities for passive ventilation largely occur over night when temperature and humidity levels are relatively low or tolerable. During mid-day when the sun’s rays are overhead and temperature rises, the building’s openings are closed and interior conditions are maintained at comfortable conditions until the active air conditioning system is prompted to take over by a rise in interior temperature. This strategy allows for nightly flushing out of heat in the building’s materials, lengthening the period of time during the day for comfortable passive ventilation and reducing energy usage by active systems.

High solar radiation is correlated with high temperature and low humidity levels during the day while at night solar radiation drops to zero and humidity begins to rise again. This shows that while night time flushing may remove latent heat, there is a possibility of humidity levels rising above tolerable levels inside the building.

Note: The temperature unit logged in Table 1 is in Celsius.
Experiment one took place from 8pm on June 6, 2015 through 8am on June 9, 2015. Weather throughout the experiment timeframe featured no rain events alongside high solar radiation exposure and variable wind speed. The operation strategy outlined at the top of the graph (Fig. 2) shows frequent passive ventilation was used for the majority time of the experiment. During peak solar radiation exposure louvers were placed over the windows to prevent heat gain only to be removed again later in the day when passive ventilation was again possible. Conditions as they were recorded by the occupant report that the interior grew too hot (27°C/ 60% RH) during midday operations and had to be supplemented with active systems. This can be seen in the bottom graph in Fig.2 when looking at the AC consumption as correlated with interior temperature and humidity.

Figure 2: Experiment 1 Operation and Environment Parameters
Experiment two took place from 8pm on June 13, 2015 through 8am on June 16, 2015. Weather during the experiment consisted of overcast skies and intermittent rain. The operation strategy that was implemented shows passive ventilation at the beginning and end with high AC use during the second day (Fig. 3). The rain event occurred around 10am through midnight on June 14th. The operation strategy shows that windows were left open during the third day (June 15th) of the experiment while the AC was running, a missed operation not planned. Comfort conditions on the interior as reported by the researcher were tolerable with high humidity, rising from 69% to 80% before the rain.
Figure 3 Operation and Environment Parameters

Weather during the experiment consisted of no rain events with moderate wind speed allowing for passive ventilation with no AC consumption for the entirety of the time (Fig. 4). Windows remained open for the entire experiment to allow for natural ventilation. The strong solar gain was mitigated with the opening of the sun space to release heat to the outside and applying louvers during high solar radiation time periods. Comfort as reported by the researcher was variable but tolerable during the passive ventilation timeframe. Occupying the space without AC required some tolerance of minor discomfort for short periods of time but was compensated by the cooling energy saving.
Experiment four took place from 8pm on July 11, 2015 through 8am on July 14, 2015. Weather during the experiment consisted of clear skies with no rain events coupled with high solar radiation and temperatures for the entire duration. The operation strategy implemented during this experiment did not include any opening of the windows for passive ventilation due to high temperatures and humidity levels outside. Outdoor conditions could bring a tolerable indoor environment between 1am and 6am on July 14 through natural ventilation, when outside temperature dropped below 25°C, RH remained around 75% and wind speed was around 3m/s. But checking live data and opening window cannot be
implemented due to the sleeping schedule of the researcher. Heat gain was reduced with the constant flushing of the sunspace as well as through use of louvers over the windows. Comfort as reported by the researcher was considered satisfactory given that use of the mechanical cooling system was relied upon for the duration of the experiment.

Experiment #5 Operation and Environment Parameters

Experiment 5 took place from 8pm on August 15, 2015 through 8am on August 18, 2015. The weather during the experiment consisted of a mixture of clear, sunny skies, high temperatures, and a rain event (August 17th night). The operation strategy implemented took advantage of passive ventilation early in the experiment at night of August 15th before switching to the mechanical cooling system. The reliance of mechanical cooling is due to
subsequent high humidity and temperatures, as well as the rain. There were so few natural ventilation opportunities between 8pm and midnight on August 16 that the researcher skipped it. Solar heat gain was reduced through the continuously flushing of the sunspace as well as placing louvers over the windows during periods of high solar radiation. Comfort as reported by the researcher was described as pleasant with much of the interior environment controlled by the mechanical cooling system for the majority of the experiment.

Figure 2 to Figure 6 show the relationship between the five environmental factors during the experiment timeframes. These charts were utilized to determine when passive ventilation was feasible comparing factors other than solar radiation and climate data. Temperature, relative humidity, and wind speed work together dynamically to produce comfortable interior and exterior environments.

The adaptive thermal comfort model was utilized after the experiment time frame to determine the operation strategies effectiveness and compliance to ASHRAE-55 (ASHRAE, 2013). The input variables include: dry bulb indoor air temperature, mean radiant temperature, prevailing outdoor mean air temperature and indoor air speed. The dry bulb indoor air temperature is averaged hourly based on measurement inside the house. Mean radiant temperature is assumed to be the same as the dry bulb indoor air temperature, because when the natural ventilation operations are in place, the solar radiation level is always low enough to avoid additional solar heat gain from the unshaded windows. And the surrounding surfaces of wall and furniture are close to dry bulb air temperature (Nicol et al., 2012). Prevailing outdoor mean air temperature is a simple arithmetic average of the outdoor air temperature in seven sequential days prior to the day in question (ASHRAE 55, 2013). And the indoor air speed is an arbitrary selection of 0.3m/s for all the plots because it’s the lowest air speed available with the plotting tool (Tyler et al., 2013) and the researcher did not report obvious feeling of air movement around body from natural ventilation. Fig. 7 includes the comfort plots when only natural ventilation was implemented for cooling and the researcher was lightly clothed and sitting and working on computers. Thus the adaptive comfort during sleeping time and AC running period is not included. By implementing this analysis across all of the experiment time frames a percentage of compliant to non-compliant operation times is developed as shown in Table 2.

Compliance with ASHRAE standard 55 during the experiments was maintained at 92% or above for the entire duration of the occupied times passively ventilating. Analysis of the individual experiments shows that experiment 4 does not occur on the plot due to reliance on the mechanical systems. Experiment 2 features the only plotted data point outside of the compliant area. Further analysis of the log shows that during this experiment night time natural ventilation was used and during that timeframe conditions became too warm resulting in noncompliant conditions. Analysis of the experiment’s data charts shows that the lab’s mechanical AC and ventilation system turned on for 100 % of experiment 4 and 80% of experiment 5 due to high temperatures and humidity levels. Examples of this can be found in figure 5, where cooling set point was set to 22.8 °C during the experiments. Strategies during these time periods of mechanical ventilation focus on mitigating the solar heat gain through transparent surfaces to reduce the amount of cooling load on the building while also opening the sunspace exterior doors to ensure heat does not build up in the space.
Figure 7: Adaptive Comfort Chart. Hourly average values during experiment timeframes (Tyler, 2013).

Table 2: Adaptive Chart Experiment Compliance Comparison

<table>
<thead>
<tr>
<th>Experiment</th>
<th>90% - 100% Compliant</th>
<th>80% Compliant</th>
<th>Not Compliant</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>84%</td>
<td>16%</td>
<td>0%</td>
</tr>
<tr>
<td>2</td>
<td>92%</td>
<td>0%</td>
<td>8%</td>
</tr>
<tr>
<td>3</td>
<td>81%</td>
<td>19%</td>
<td>0%</td>
</tr>
<tr>
<td>4</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>5</td>
<td>100%</td>
<td>0%</td>
<td>0%</td>
</tr>
</tbody>
</table>

5 Energy Simulation
An energy model was trained to predict the energy savings from experiment operations. DesignBuilder V4.5 was used as the simulation interface with EnergyPlus V8.3 as the simulation engine.

Since the experiments were carried out from June to August, 2015, the measurement data in the same three months are selected to train the energy model. 92 days of AC unit performance data from June 1 to August 31, 2015 are divided into 3 groups: stable AC control for 52 days, unstable AC control for 35 days and unreliable measurement for 5 days.
During the stable AC control period, the AC schedule is set to be: occupied mode is on from 7:01am to 7:00pm, and the cooling set point is 22.8°C; Unoccupied mode is from 7:01pm to 7:00am of the second day, and the cooling set point is 26.7°C. In the unstable AC control period, the AC set point ranges from 21.7°C to 23.3°C with irregular occupied timestamps and occupancy loads. All the experiments happen in the unstable AC control period, when the researcher could override the default cooling control and adjust it for energy saving and comfort purpose. And during the unreliable measurement period, due to system maintenance a lot of data was either missing from the records or showed extreme outliers, making the measurement not suitable for this research application.

To develop a prediction tool, first the data from stable AC control period is used to train the AC cooling simulation model. After getting a satisfied result from the model training, the occupancy schedule of experiments is updated in the building energy model according to experiment logs, for the occupancy of the building is changed during experiment from an office schedule to a mix usage of residence and office. The simulation result of this updated model gives AC cooling consumption that could have been used without passive strategy intervene. The difference between simulated and measured AC consumption is considered to be a result of the passive strategy operation.

The total daily AC cooling consumption from trained energy model results in a Normalized Mean Bias Error (NMBE) at 6.45% and Coefficient of Variance of Root Mean Square Error (CVRMSE) at 28.30%. These two statistic indices indicate a reliable model for small house energy consumption prediction.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Day</th>
<th>Simulated Cooling without operation =S (Wh)</th>
<th>Measured Cooling with operation =M (Wh)</th>
<th>Simulation without Error SE=S/(1+NMBE) (Wh)</th>
<th>Simulation Standard Deviation SSD=SE*CVRMSE (Wh)</th>
<th>Possibility of Yielding Cooling Saving from Experiment Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>1</td>
<td>7434</td>
<td>5321</td>
<td>6984</td>
<td>1976</td>
<td>80%</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>6707</td>
<td>6323</td>
<td>6301</td>
<td>1783</td>
<td>49.5%</td>
</tr>
<tr>
<td>#2</td>
<td>3</td>
<td>8448</td>
<td>5759</td>
<td>7936</td>
<td>2246</td>
<td>83.3%</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>4265</td>
<td>6121</td>
<td>4007</td>
<td>1134</td>
<td>3.1%</td>
</tr>
<tr>
<td>#3</td>
<td>5</td>
<td>5216</td>
<td>0</td>
<td>4900</td>
<td>1387</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>7699</td>
<td>0</td>
<td>7233</td>
<td>2047</td>
<td>100%</td>
</tr>
<tr>
<td>#4</td>
<td>7</td>
<td>15498</td>
<td>13799</td>
<td>14559</td>
<td>4120</td>
<td>57.3%</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>15589</td>
<td>13472</td>
<td>14644</td>
<td>4144</td>
<td>61.1%</td>
</tr>
<tr>
<td>#5</td>
<td>9</td>
<td>12561</td>
<td>11994</td>
<td>11800</td>
<td>3339</td>
<td>47.7%</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>10898</td>
<td>9550</td>
<td>10238</td>
<td>2897</td>
<td>59.4%</td>
</tr>
</tbody>
</table>

All the five experiments approximately start from Saturday night 8pm to Tuesday morning 7am for a 60 hour time period. In the following comparison between simulation and measurement, the 24 hour period from Sunday 00:01 to Sunday 24:00 is considered as Experiment Day #1, Monday 00:01 to Monday 24:00 is considered as Day #2, and so on.

Among all the 10 experiment days (Table 3), Day #4 is most likely not yielding any energy saving from the passive operations, and then followed by Day #2 and Day #9 where the
possibility of saving energy through operation is slightly lower than 50%. The reasons are analyzed based on the logs and DAS measurements as followings.

For Day #4, it was raining during the night of Experiment Day #3 and the researcher lowered the cooling set point by 1.2°C around 7pm (Fig. 3). Both the exterior high humidity and interior lower cooling set point result in a continuous AC cooling consumption overnight. And during day time, the researcher missed to close the windows while AC was still running. These operations are not yielding any energy saving. It could even cause a higher energy consumption for the total value of a whole day. And when compared with the simulation prediction, the energy saving possibility is found to be very low from these operations.

![Graph](image)

**Figure 8**: Comparison between Simulation and Measurement Results with NMBE and CVRMSE of the Trained Model

On experiment Day #2 (Fig. 2), the researcher utilized natural ventilation in the morning when outside humidity was between 60% to 80%. The highly humid air stayed in the house until AC was turned on around noon to start cooling both the dry air and moisture from a condition of 24.7°C/62% RH to 21.2°C/53% RH. During the AC cooling period, a hot water shower was taken in the house and added extra heat and moisture to the cooling load.

Before 11am on Day #9 (Fig. 6), the AC was turned off and windows were opened to bring in the exterior air around 22.8°C/ 70% RH. The log reports from the previous night till morning natural ventilation bringing a very humid and uncomfortable environment inside (outdoor RH above 80% and indoor RH between 50%-60%). And thus when the indoor air temperature rose to 26°C and the researcher started AC around 11am, a lot of extra energy need to spend on cooling down the humid warm air.

The most successful cases which have high possibility of energy savings are on day #1, 3, 5, 6. On Day #1 although the RH was high as well, there was a sudden outdoor air temperature drop to about 20°C around 3pm (Fig. 2), and AC load was immediately decreased at that time. In addition, nobody was showering when AC was on.

On experiment Day #3 (Fig. 3), although the humid air was brought in through natural ventilation, both the indoor and outdoor air temperature was below cooling set point when windows were open. The air humidity adds thermal mass to slow the speed of indoor air temperature increase. On Day #5 and #6 (Fig. 4) the AC was not turned on at all and the researcher managed to keep the condition within comfort range during the whole experiment #3.
Comparing different operation strategies together, it appears that the energy savings impact of shading and sunspace configuration is not as obvious as natural ventilation. On experiment Day #7, #8 and #10 (Fig. 5 and 6), when AC system was constantly on without natural ventilation, operations of changing the shading and sunspace opening configuration result in a possibility of energy savings at about 60%.

Summarizing the results of all experiments suggests that outdoor air humidity should be considered in conjunction with outdoor air temperature and indoor cooling set point to decide when to utilize natural ventilation. During a typical humid summer day when natural ventilation and mechanical cooling might alternate in rapid sequence, natural ventilation should be discontinued before the exterior air temperature reaches the indoor cooling set point to achieve maximum energy savings. If warmer humid air is brought into the house, it’s possible, that natural ventilation will result in some energy increase instead of cooling saving.

6 Conclusion and Future Work
Through detailed monitoring of environmental conditions and buildings components, operation strategies are developed for reducing energy costs and maintain human comfort. Metrics of this nature allow for performance benchmarking while also providing direct feedback to users in regards to how their behaviours affect energy usage. Real time data collection and feedback to occupants allows for informed decision making that reduces energy consumption by prompting changes in behaviour before an individual becomes physically uncomfortable. Developing models to better measure and predict these variables leads to improved building interfaces and energy efficient operation strategies for building users.

The understanding of passive operation strategies is improved through this experimental process. For a warm and humid climate, implementing natural ventilation could bring in moisture as well, which results in either cooling energy savings or increases, depending on the relation of the temperature difference between exterior humid air and indoor cooling set point.

The high variability of factors relating to local weather and interior conditions coupled with the effort needed to monitor and operate the building have aided in the understanding of building operation strategies. An use of programmed monitoring and mechanically operated openings could make improvement through removing operation errors caused by occupants, and yielding additional energy saving by allowing for a longer operation period during times of sleep. Implementation of these technological components must be done with additional investigation on the potential energy saving through smart control alongside the extra energy consumed by using a mechanical system for smart control.

Other passive strategies of operating shading and spatial configuration are promising methods to save cooling energy, but for a limited operation length and unstable outdoor weather condition, the result is not as obvious as natural ventilation. To quantify the amount of energy saving by the passive strategies, it is necessary to improve the model accuracy and precision for a better prediction.
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