

DESIGN AND MODELING STRATEGIES FOR RETROFIT TO NATURAL VENTILATION.

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ABSTRACT

This paper presents the simulations used in designing a major retrofit to a fully conditioned office and classroom building on the University of Hawaii campus so that it is comfortable without air conditioning (compressive cooling). The design and consulting team worked with lighting, daylighting, shading, thermal mass and ventilation strategies so that comfortable conditions are expected to be maintained in classrooms and faculty offices. We developed modeling strategies to work iteratively with the design process to ensure that comfortable conditions can be achieved. This paper specifically describes the modeling strategies used to simulate adaptive comfort algorithms, cross-ventilation modeling, wind tunnel testing and calibration using site weather data.

INTRODUCTION

Kuykendall Hall at the University of Hawaii at Manoa (UHM) was constructed in 1964 and consists of a four story classroom building of 56,000 sf and a seven story faculty office building at 20,000 sf, linked by a multistory, naturally ventilated bridged walkway.



Figure 1. View of Classroom Building In The Foreground And Faculty Building In The Background

The classroom building is a four story concrete structure consisting of classrooms, computer rooms,

electronic equipment rooms, administrative offices, and an auditorium. The first floor includes teaching equipment support offices, faculty development offices, and a 210-person auditorium. Part of the second floor has special equipment and teaching classrooms for Information Technology. The faculty building is a seven story building and has a compact floor plan with a core of two staircases, bathrooms and utility space bordered by private offices. In the early 60's, Kuykendall Hall was originally built as a naturally ventilated building. Corrosion of the jalousie window mechanisms and acoustic problems led to the 1987 renovation which introduced air conditioning and eliminated more than two thirds of the glazing from the classroom building. The two air conditioned buildings currently use about 894,500 kWh annually.

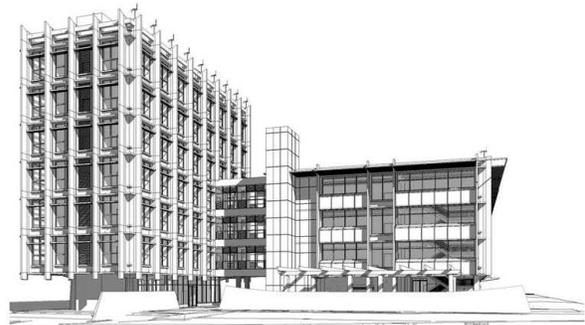


Figure 2. Rendered Views Of Proposed Design

After an analysis of different strategies, UHM chose to pursue an overall design that emphasizes natural ventilation and ceiling fans for cooling and comfort. This option is best able to reduce energy demand while meeting occupant requirements by capitalizing on the local prevailing winds, using ceiling fans to reduce demand for mechanical cooling, shading the windows and relying on daylighting to reduce demand for electric lighting energy. Apart from the first floor of the classroom building which has high internal loads, the rest of the project relies on natural ventilation to maintain comfortable conditions, and is occasionally

assisted by mechanical ventilation when on-site air movement is insufficient in providing adequate air changes for comfort. In both wings of the project, a night time dehumidification system is employed to interrupt any potential mold cycle. The modeling strategies had two objectives here. One was to model in an explorative manner so as to arrive at the design solution. The second was to analyze the design to understand the energy implications.

Some of the literature on natural ventilation (Fry and Drew, 1982) describes traditional strategies of getting ventilation in a building under different climatic conditions. More recent articles (Brager and de Dear, 2000) cover comfort and ventilation, specifically adaptive comfort. Simulation software manuals describe simulation of ventilation and its effect on the conditions in the space. This paper brings a number of these ideas together by simulating comfort conditions in the space and then simulating the control of ventilation so as to achieve adaptive comfort. Simulation engines do not directly model this process and multiple simulation runs have to be layered to arrive at the final results.

SIMULATION

Overview of modeling Strategy

This subsection describes the broad outline of the modeling sequence used in this project.

- Adaptive Comfort algorithms described in ASHRAE 55-2010 Standard are used as a basis for the comfort analysis.
- Adaptive comfort algorithms use Dry Bulb Temperature (DBT), Relative Humidity (RH), and Mean Radiant Temperature (MRT) as input variables. DBT, RH and MRT were generated with hourly outputs of the EnergyPlus simulation of the building.
- Parametric sensitivity analyses using varied levels of ventilation air changes were used to identify the optimal air change rate to deliver thermal comfort.
- Wind tunnel tests were performed to check and modify the design to ensure that the optimal air change rate was achievable.
- The speed and pressure measurements from the wind tunnel allow us to correlate the site wind conditions to the simulation of air changes in the spaces studied.
- This air change rate was then input back into the EnergyPlus model to generate the hourly comfort algorithm inputs of DBT, RH, MRT.

- These inputs were applied to the comfort algorithms to produce the interior annual hourly comfort conditions.
- Hours of discomfort indicate when site wind conditions were insufficient for comfort and powered ventilation is required.
- The modeling allows us to simulate when the ventilation fans had to come on and at what speed, to make for shortfall in wind driven ventilation.
- Control algorithms for the fans were then based on strategies used in the modeling.

Adaptive Comfort

The concept of adaptive comfort is that the comfort zone, or range of acceptable indoor temperatures, drifts upwards in warm weather and downwards in cooler weather. This is particularly true in situations where occupants have control over their environment (e.g., flexible dress codes, control of operable windows or other devices). The comfort chart depicted in Figure 3 is taken from ASHRAE Std 55-2010 (ASHRAE 2010). The percentages in the diagram can be explained in the following manner: an indoor operative temperature falling within the 80% range should be regarded as acceptable or satisfactory to at least 80% of building occupants who are exposed to it, and the tighter 90% acceptable temperature range is likely to satisfy 90% of occupants.

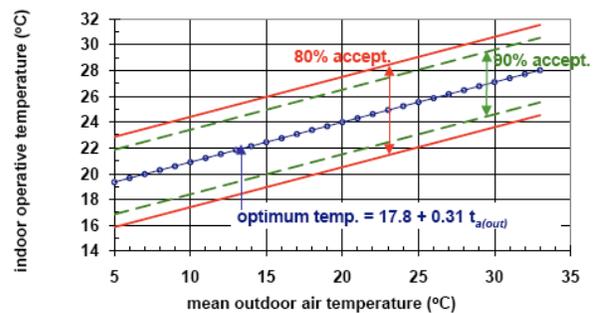


Figure 3: The ASHRAE Std 55-2010 adaptive comfort standard as a function of prevailing outdoor temperature. $t_{a(out)}$ is the arithmetic average of the mean monthly minimum and maximum daily air temperatures for the month in question.

The equation for the Upper 80% Acceptable Limit is:

$$\text{Upper 80\% Accept.} = 0.31 t_{a(out)} + 21.3 \text{ } ^\circ\text{C} \quad (1)$$

ASHRAE's adaptive comfort was defined using the mean monthly dry bulb temperature and does not take into account the effect of humidity on comfort. Manoa in Hawaii has high humidity that will affect the comfort. In the original ASHRAE research project (RP-

884) that led to the development of the adaptive comfort standard, mean outdoor effective temperature (ET*) was used to arrive at the comfort zone (de Dear and Brager 1998). ET* (ET-star) is defined as the temperature at 50% relative humidity which would cause the same sensible plus latent heat exchange from a person as would the actual environment. ET* values can be calculated using WinComf© (Fountain and Huizenga 1996). If ET* is used instead of dry bulb temperature, we get a modified graph shown below. Humidity has a significant impact on comfort. Starting at 26°C if the humidity increases from 20% RH to 80% RH the air temperature has to drop by about 2°C to maintain an equal level of comfort. In other words, the temperature has to drop by 2°C to maintain the same ET*.

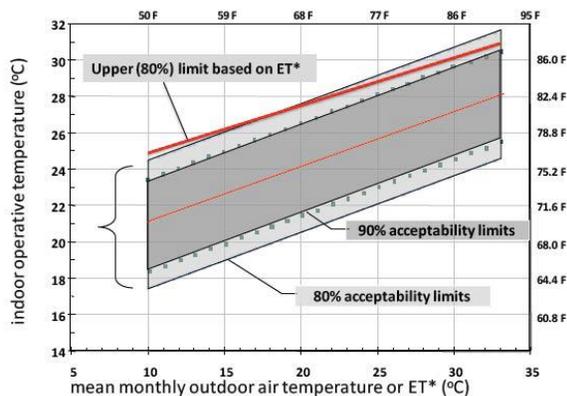


Figure 4: The ASHRAE 2010 adaptive comfort standard in naturally ventilated spaces showing the upper (80% acceptability) limit based on mean monthly ET*.

When using ET*, the optimum indoor temperature is given as:

$$\text{optimum indoor temperature} = 18.9^{\circ}\text{C} + 0.255 * (\text{outdoor mean ET}^*) \quad (2)$$

Acceptable temperature ranges around the optimum in naturally ventilated buildings were specified as $\pm 3.5^{\circ}\text{C}$ for 80% acceptability and $\pm 2.5^{\circ}\text{C}$ for 90% acceptability. This corresponds to the two acceptability deadbands shown in Figure 3.

At the time this project was done in 2011, there was a proposed addendum to Std 55 to take in to account impact of airspeed on comfort. In this addendum, an increase in airspeed increases the acceptable operative temperature limits as shown in Table 1.

Table 1 Increases in Acceptable Operative Temperature Limits (Δt_o) in the Adaptive Comfort Standard resulting from Increasing Mean Air Speed Above 0.3 m/s (59 fpm).

Mean Air Speed = 0.6 m/s	Mean Air Speed = 0.9 m/s	Mean Air Speed = 1.2 m/s
1.2°C (2.2°F)	1.8°C (3.2°F)	2.2°C (4.2°F)

This project uses the upper 80% acceptable limit, with an airspeed of around 1 m/s, always available through ceiling fans, allowing us to increase the acceptable temperature by 2 degrees C.

From EnergyPlus Outputs to Adaptive Comfort - Comfort Spreadsheet

EnergyPlus version 6 was used to simulate all the zones in the buildings. For each hour in each zone the simulation outputs give us dry bulb temperature (DBT) and mean radiant temperature (MRT). Both MRT and DBT affect the comfort and we can combine it into a single value called Operative Temperature (OT). The average of MRT and DBT is OT. Now we need to find out if this operative temperature lies within the comfort zone. We are using equation (2) to calculate upper bound of the comfort zone. ET*, needed in equation (2), was calculated using the software WinComf. The DBT and relative humidity (RH) from the weather tape go into WinComf which returns ET*. Batch processing was used to calculate ET* for every hour of the year. From this we can calculate the mean ET* for the month. Instead of calculating the mean for the month, we calculated the average ET* for the previous 15 days, since the person is acclimatized by the conditions of the previous days. Once we have ET*, equation (2) helps us get to the 80% acceptable temperature for that hour or day. Now we can test if the operative temperature is outside the comfort zone and by how much. A spreadsheet was used to calculate this for the entire year. We call this the **Comfort Spreadsheet** and we use it many times in later steps of the modeling process.

Visualizing Comfort

The spreadsheet in the previous sub-section provides the level of comfort or discomfort for every hour. A simple metric is to count the number of discomfort hours in a year. If there are no discomfort hours, there is nothing more to be done. If there are discomfort hours, several questions arise - what is the number of discomfort hours, when do they occur and how far out of the comfort zone are those hours. To see this visually we draw a “heat map” of comfort as shown in figure 5.

(Most spreadsheets can draw such a “heat map”)

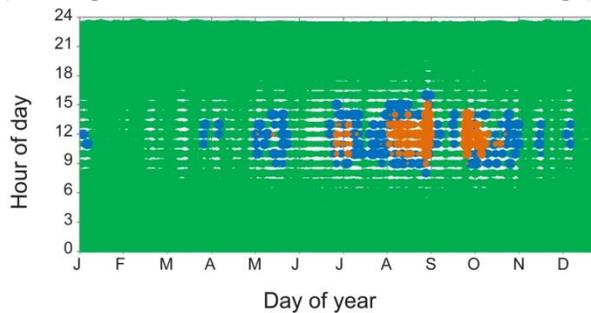


Figure 5. Heat map of comfort hours

The x-axis maps the days of year from January 1st to December 31st. The y-axis maps the 24 hours of the day. This gives us 8760 (24 hours \times 365 days) points on the chart. In figure 5, each hour within the comfort zone is colored green. If the hour was close to the comfort zone (1°C from the threshold of discomfort), it is colored blue and if it is outside the comfort zone, it is colored orange. The size of the dot indicates how far inside or outside the comfort zone it is. Now we can quickly look at all zones and see how they are performing.

Optimizing Air Changes for Comfort

Natural ventilation brings about comfort by 1) air movement on the skin and 2) by air changes that displace the warm stale air in the room whenever the air outside is cooler than the air inside. To simplify our analysis, it was assumed that natural ventilation would only increase comfort through air exchange with the exterior; any effects related to increased air movement on the skin would be ignored. This may underestimate comfort levels, but it increases confidence that a given air change rate will produce conditions that are at least as comfortable as expected.

The question here is how many Air Changes per Hour (ACH) are needed to bring about comfort. Multiple simulations were done with ACH ranging from 1 to 30 ACH for all zones. The ACH is controlled in the simulation so that ACH just enough to maintain indoor air quality when conditions outside are too hot. The comfort heat maps of the zones were examined to see how the building performed. It was apparent from this analysis that air change rates greater than 10 ACH do not bring about much improvement in comfort. So in the modeling no attempt was made to have air changes greater than 10 ACH.

Design for Thermal Comfort

Even with 10 ACH several zones were showing unacceptable levels of discomfort. Sensitivity runs were made to see the effects of thermal mass, internal loads,

sunlight penetration and insulation. Analysis showed that the comfort levels were very sensitive to internal loads, sunlight penetration and roof insulation. There was fair sensitivity to exposed thermal mass and low sensitivity to wall insulation. Based on this understanding, structural concrete slabs were left as exposed ceilings and floors, allowing effective radiant exchange between the thermal mass of the concrete and the occupants of the building. The partition walls were made with two layers of gypsum board rather than one for additional thermal mass. Exterior shades were designed to prevent nearly all direct sun penetration. Daylighting was optimized using RADIANCE simulations in order to minimize electric lighting use during daylight hours. Aggressive energy efficiency goals were established for electric equipment in all zones. This lowered the internal loads. Finally, roof insulation was increased. With these changes, discomfort hours were reduced to acceptable levels.

Design for Ventilation

The classroom building has a double loaded corridor layout. This makes it difficult to get cross-ventilation since only one side of each classroom is exposed to the outside. The proposed solution is to let outside air come in through a louvered sound attenuation box beneath the window and allow it to leave the classroom via a duct that runs over the opposing classroom and out the other side of the building. The air could flow in either direction. This is illustrated in Figure 6 below.

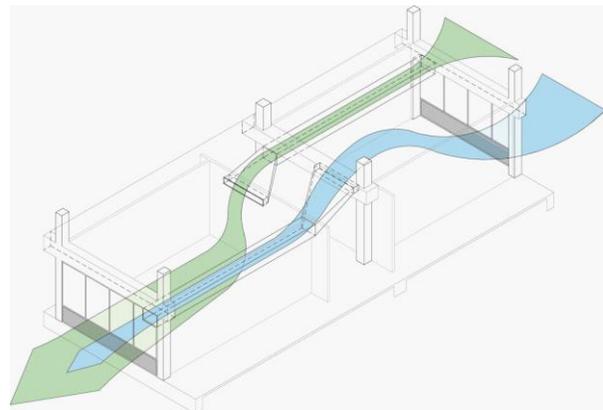


Figure 6. Ventilation pattern in classroom building

In the original office tower, the offices were on the periphery with and the building core has utility spaces. There were two corridors that ran almost the entire length of the building and were open to the outside on one end, but terminated at an office on the other end. For the remodel, the corridors were extended to run the entire length of the building and to be open to the outside at both ends. The idea here was to let outside air come in through the office windows, pass through

the corridors, and leave the building (or move in the reverse direction). The office ventilation is shown in figure 7. There is a clearstory duct that lets the air move between the office and the corridor.

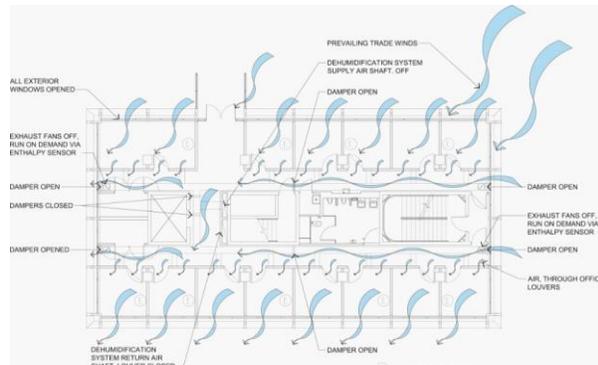


Figure 7. Ventilation pattern in office building

Both the classroom and the office tower have sound baffles at the window inlet for acoustic protection from outside noise.

Wind Tunnel Testing

Since the performance of the ventilation was critical to the project, a phase of our analysis was dedicated to testing whether we could achieve the required rates of ventilation with the proposed design. While a similar design analysis could have been performed with research-grade CFD analysis, we chose to perform wind tunnel testing since we knew the results would be physically traceable. The study utilized the boundary layer wind tunnel at the Building Science Laboratory in UC Berkeley. We tested a massing model that included the site context within about 600 ft. of the building, and detailed models to study air flow within specific areas of the building. Models were placed on the wind tunnel turntable and tested under 9 different wind directions.

There were two purposes to the wind tunnel testing. The first was to try out alternatives in the wind tunnel and explore design options. The second was to be able to calculate the air change rate in each room. The wind tunnel testing enabled us to calculate expected air change rates as follows:

1. Determine pressure coefficients at openings for a reference wind velocity and for different wind directions.
2. Determine air flow through transfer ducts in individual zones at measured exterior pressure differences.
3. Calculate air change rate using measured air velocity in the transfer duct, the cross-sectional area of the transfer duct, and the zone volume.

Generating this information allowed us to build up a lookup table with a factor for all the wind directions (0° to 159° , with $N=0^\circ$). Multiplying the outside air velocity by the factor in the lookup table would give us the air velocity in the room or duct. Once we have the air velocity, we could calculate the air change rate in the room.

The wind tunnel was critical in fine tuning the ventilation configuration and ensuring that the design would actually deliver the expected air changes. In the classrooms, the wind tunnel tests showed that the exterior louvered opening for the outlet duct had to be increased by six inches to deliver the required air change rate. In the office tower, we began with an initial strategy of leaving both ends of the corridors open, and letting the air flow through them. Under this configuration, the wind tunnel testing showed that several rooms became dead zones with very little cross ventilation. As we explored alternative configurations, we discovered that if the long corridors were closed at one end and left open at the other end, all the rooms got sufficient ventilation. The prevailing wind would come into the corridor and pressurize the corridor. This pressurization would push the air into all offices adjacent to the corridor. If the wind came from the other direction, the corridor would get de-pressurized and it would draw air from the offices, allowing a flow in the opposite direction.

From wind tunnel to EnergyPlus

The lookup tables described in the previous subsection provided the ACH in a zone, given a specific exterior wind velocity and direction. Using a spreadsheet, we combined this lookup table with hourly wind direction and wind velocity data extracted from a weather file. (EnergyPlus version 6 outputs the wind direction incorrectly, forcing us to get it directly from the weather file). The spreadsheet was configured to generate the hourly ACH for all the zones. The hourly ACH was then saved as CSV file. This CSV file was then used as a schedule input in EnergyPlus in order to mimic the air changes due to natural ventilation.

Ceiling Fan modeling

The next step in the modeling was to add the effects of ceiling fans. It was assumed that the ceiling fans would produce an air velocity of 1 m/s, which would increase the upper limit of the comfort zone by two degrees celsius. For simplicity of modeling, we are assuming that there are no other sources of increased air velocity. In reality, limited increases in air velocity could also be caused by natural and fan-powered ventilation. In the model, the ceiling fans will come on only when needed and will turn off when not needed. So how do we find

out when the ceiling fans should be running? We use the "Comfort spreadsheet" mentioned in an earlier subsection and use it to identify the hours the the room would be outside the comfort zone without air movement, but with air changes from natural ventilation. To model the use of ceiling fan during these discomfort hours, we again used CSV files to input custom schedules into EnergyPlus. These schedules simulated the energy use of the ceiling fans, as well as the internal heat gain due to the ceiling fans.

Powered ventilation design

There are times when the wind velocity is too low to bring about adequate ACH for comfort. At these times, fan powered ventilation is used to get the required ACH in the rooms. The powered ventilation is configured like a standard VAV system, except that the air is drawn in the reverse direction. Air is drawn through the window into a VAV box and exhausted out. This allows us to modulate the air flow such that the ACH is just sufficient to bring about comfort. The VAV boxes are controlled by an "operative temperature" thermostat that looks at the average value of the DBT and MRT in the room. This thermostat is also an "adaptive comfort" thermostat, as it bases its setpoint in relation to the exterior DBT and RH conditions over the last fifteen days. The system is powered by a variable speed fan, that changes its speed based on response to a pressure sensor in the duct.

Powered ventilation modeling

It was not possible to do the powered ventilation in a single energy simulation run. Multiple simulations had to be run to build up the pattern of the fan powered ventilation. The process by which this is done is to identify the hours of discomfort and then slowly increase the ACH at the hours of discomfort until comfort conditions are achieved. The steps to do this are described below:

1. Run the first model with no powered ventilation.
2. Putting the results of the first model into the comfort spreadsheet will tell us which hours are outside the comfort zone. At the same time we know the ACH due to natural ventilation in those rooms.
3. Powered ventilation in the rooms with discomfort is increased for the hours of discomfort. The powered ventilation would be 1 ACH more than the ACH due to natural ventilation, and would replace the natural ventilation. This would be the next simulation run.
4. The outputs of the simulation run in the previous step are analyzed using the comfort spreadsheet to get the hours of discomfort. Now there will be

fewer hours of discomfort, since the ventilation has increased.

5. Powered ventilation in the rooms with discomfort is increased by 1 ACH for the hours of discomfort. This would be 1 ACH more than the ACH in the previous simulation run.
6. Repeat step 4 and step 5 until there are no more discomfort hours or if until the air changes is equal to 10 ACH.
7. Once the condition in step 6 is met, the resultant model would be the final model with the least discomfort hours. This model will have the final schedule of the powered ventilation.

Steps 4, 5 and 6 can be done by using a spreadsheet as pre-processing between the two simulation. In our case we used a pre-release version of eppy - a scripting language for EnergyPlus (Philip, Tran and Tanjuatco 2011) to automate this process

Modeling of final design

The final energy model embodies certain elements that were not discussed in the previous subsections. This includes the following:

- About four hours of night time dehumidification are modeled for every other night, which serves to interrupt the mold growth cycle if any.
- The classroom wing is designed to maintain the corridors at a slightly lower temperature by active mechanical cooling to provide initial relief for arriving students and provide benches for them to pause and relax before class. This tempering of the air is included in the model.
- One of the floors is modeled as fully conditioned due to high internal loads in rooms on that floor.

All the elements described in the previous subsections are part of the model. These include:

- the natural ventilation modeled as scheduled air changes in the room
- ceiling fans scheduled to come on whenever needed to raise the upper limit of the comfort zone
- powered ventilation scheduled to come on whenever natural ventilation is not meeting the comfort demands. The volume of the powered ventilation is modulated by the comfort requirements.
- The lights coming on whenever the daylight is insufficient. The electric lights are scheduled based on RADIANCE simulations of daylighting.

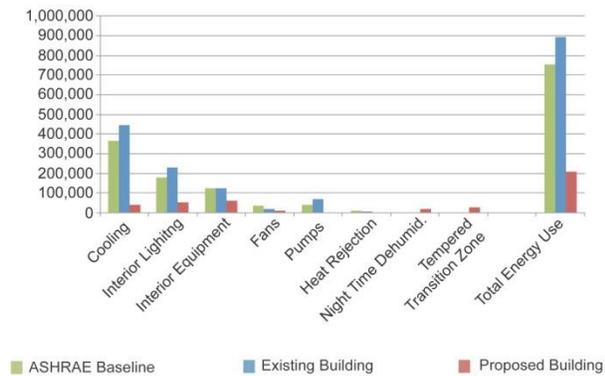


Figure 8: Expected Energy End Uses for the ASHRAE building, the existing building and the proposed buildings.

With all the above elements we are able to calculate the full energy use of the building as illustrated in the chart below. The chart shows the retrofitted buildings' energy use in relation to the present energy use of the building as well as the energy use of the building modified to meet the ASHRAE 90.1-2007 standard (ASHRAE 2007). Normally one would not compare an unconditioned building to a conditioned ASHRAE baseline building. But in this case it was informative to do so, since we are converting a conditioned building into a naturally ventilated building.

The model was initially run with the TMY3 airport weather file as well as data from a weather station close to the site. Later the building was monitored for an entire year by a weather station on the roof of the building. This monitored weather data was also used to simulate the energy use of building. The airport weather data gave more discomfort hours than the weather stations at or near the site.

DISCUSSION

Performing simulations in support of natural ventilation design required a series of models with incremental modifications. The process can be viewed as a series of EnergyPlus models, where the outputs of one model act as input modifications to the next model. The model outputs have to be processed before they can be used to modify the next model. Even though this process was done here for a specific project, there are many common elements that can be abstracted out for use in any project:

- Put together a "Adaptive Comfort Spreadsheet", that will generate the discomfort hours for all the rooms. This spreadsheet will use the local weather data and operative temperature of the rooms. This spreadsheet will be used in all the steps below.

(This spreadsheet is not needed if EnergyPlus can output adaptive comfort data and discomfort hours)

- Find the maximum effective air changes for comfort. ACH above this value will have minimal effect and there is no need to exceed it. This maximum ACH may be dependent on building configuration and climate. Further research is needed to discover if the 10 ACH used in this project is generic and can be used in other projects.
- Modify the building design to reduce the number of discomfort hours with the maximum effective ACH (10 ACH in this project)
- Run the model with natural ventilation. For a simple geometry, model the ventilation directly in EnergyPlus. For more complex geometry, if resources are available, use external modeling (wind tunnel or computer fluid dynamics analysis) to generate ACH or pressure coefficients, that can be then input into an EnergyPlus model. Extract the discomfort hours from this model
- Use the discomfort hours to evaluate when the ceiling fans will turn on. Incorporate this into the next model. This step can be skipped if EnergyPlus has an adaptive comfort thermostat that can control ceiling fans
- With a series of models, incrementally increase powered ventilation until comfort is achieved for all the discomfort hours. This step can also be skipped if EnergyPlus has an adaptive comfort thermostat that can control powered ventilation.

In the above steps, some potential EnergyPlus enhancements have been identified. This paper can be used as a foundation to develop specifications for these enhancements. The enhancements are listed below:

- output reports that give adaptive comfort data as well as discomfort hours
- adaptive comfort thermostat that can trigger and control powered ventilation
- adaptive control thermostat that can trigger and control ceiling fans
- ET* can be included in the adaptive comfort calculations for use in humid climates.

The wind tunnel testing in this project seemed to indicate a method for ventilation deep within large buildings. In the office tower, closing off one end of the corridors allowed pressure to build up within the corridor. This pressurization was pushing the air flow into the rooms next to it. This was an unexpected solution, and the wind tunnel test were showing it to be surprisingly effective. Extrapolating on this method, ducts or corridors can be used to bring ventilation into

deeper parts of the building. Ducts on the windward side of the building will be pressurized and the ducts on the leeward side of the building will be de-pressurized. Zones with no exterior exposure can be naturally ventilated by the pressure difference between the two ducts. When there is no wind, the same ducts can be used for powered ventilation. This method may be especially effective in tall buildings with good wind exposure.

The construction of this retrofit has been delayed. It is hoped that the building is completed in the near future, as plans are in place to monitor this building and fine tune its operation. This will allow us to validate the design methodology, modeling methods and control protocols. This building is meant to act as a model to the retrofit of other buildings on University of Hawaii campuses.

CONCLUSION

This study indicates that large buildings can be made comfortable through natural ventilation, with some powered assist when needed. Once this building is completed and monitored, there will be a greater confidence level in the process. With some research and development it will be possible to apply this methodology generically to other buildings. This study also points to useful enhancements to EnergyPlus.

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NOMENCLATURE

Air Changes per Hour – ACH

Dry Bulb Temperature - DBT

Mean Radiant Temperature - MRT

Operative temperature - OT

Relative Humidity – RH

University of Hawaii, Manoa - UHM

REFERENCES

- ASHRAE (2007). ANSI/ASHRAE Standard 90.1-2007 - Energy Standards for Buildings Except Low-Rise Residential Buildings. Atlanta, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
- ASHRAE (2010). ANSI/ASHRAE Standard 55-2010 - Thermal Environmental Conditions for Human Occupancy. Atlanta, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
- Brager, Gail; & de Dear, Richard. (2000). A Standard for Natural Ventilation. ASHRAE Journal. UC Berkeley: Center for the Built Environment. Retrieved from: <http://escholarship.org/uc/item/3f73w323>
- de Dear, R. J. and G. Brager (1998). "Developing an adaptive model of thermal comfort and preference." ASHRAE Transactions 104(1A): 145-167.
- Fountain, M.E. and C. Huizenga (1996). "WinComf : A Windows 3.1 Thermal Sensation Model - User's Manual." (Berkeley: Environmental Analytics).
- Fry, M and Drew, J (1982) Tropical Architecture in Dry and Humid Zones, Second Edition: 46-47
- Philip, S., Tran, T., Tanjuatco, L. (2011). eppy: scripting language for E+, EnergyPlus (version 0.4.6) [Software - GNU AFFERO GENERAL PUBLIC LICENSE] Available from <<https://pypi.python.org/pypi/eppy/0.4.6>>, <<https://github.com/santoshphilip/eppy/tree/r0.46>>