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Indoor environmental quality, adaptive action and thermal comfort in naturally ventilated and mixed-mode buildings

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Indoor Environmental Quality, Adaptive Action and Thermal Comfort in Naturally Ventilated and Mixed-mode Buildings

A comparison between a mild and a hot-dry climate

By

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Dr. Hui Zhang
Professor Joan Walker

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Chapter 1: Introduction

1.1. Problem statement

Air conditioned buildings are known to maintain a narrow band of indoor temperature, consuming enormous amount of energy due to overcooling of the space while not guaranteeing thermal comfort (Mendell and Mirer 2009, Zagreus 2004). In addition to this, symptoms of sick building syndrome have been observed in air conditioned (AC) buildings (Burge 1987, Seppanen and Fisk 2004). Naturally ventilated (NV) buildings on the other hand ensure adequate air changes and the indoor temperature conditions float over a wider range. These NV buildings consume 45-70% less energy than their AC counterparts (Bunn and Cohen 2001). Thermal comfort studies in NV buildings have also shown that occupants are comfortable in this wider band of indoor temperatures. Field studies to evaluate comfort in NV buildings have been greatly bolstered by the advent of the adaptive comfort theory (de Dear and Brager 1998, Nicol and Humphreys 2002). The adaptive theory posits that "occupants tend to adjust their behavior to move towards comfort" and the adaptation is further classified as "behavioral", "psychological" and "physiological".

These adaptations are heavily influenced by climate, culture and the underlying expectation of comfort, and therefore it is important to understand these differences in adaptation between different locations. In this thesis indoor air quality, adaptive actions (operating fans and windows) and thermal comfort is compared between the mild climate of Alameda in California and the hot-dry climate of Jaipur in India.

In mild climates, such as Alameda, it is often seen that buildings are air conditioned even when the outdoor conditions are perfect for natural ventilation. To understand whether NV buildings would provide comfort in a mild climate, there is a need to evaluate indoor conditions and occupant response. The Alameda case study building is one of the few NV buildings in the bay area with both operable windows and ceiling fans. The goal here is to analyze the indoor environmental conditions, clothing adjustment, window and fan usage and occupants' thermal comfort opinion during summer and winter.

In the hot-dry climate of Jaipur the goals are similar to Alameda but have a slightly different context. In India, air conditioner sales are rising and a majority of the buildings are yet to be built. A study by LBNL estimates that almost 70% of the commercial buildings that will be there by 2030 is yet to be built (Singh et.al. 2013). If air conditioners continue to be used indiscriminately in these buildings, it will mount unrealistic pressure on India's power plant. Thermal adaptation and comfort will play a key role in the new constructions that are going to come up in cities like Jaipur. Previous studies done in NV buildings in climates similar to Jaipur have found that occupants are comfortable in a wider range of indoor temperatures and mainly use fans to keep themselves comfortable (Feriadi and Wong 2004, Indraganti 2010). However, the upper limits under which the indoor temperature conditions can deviate without causing discomfort are not very well known. Moreover, the pattern of window and fan usage is not characterized. Thus there is a need to evaluate the indoor environmental conditions, comfort opinions and adaptive actions of occupants in the existing NV buildings in order to influence the design of new construction.

Although naturally ventilated buildings are gaining popularity, it is commonly seen that buildings are not always fully naturally ventilated, but sometimes combine both natural ventilation and mechanical cooling; these are referred to as 'mixed mode' (MM) buildings. The temporal and spatial method of cooling the space further classifies the mixed mode building as changeover, zoned and concurrent type (Center for the Built Environment website). Typically in office buildings in India, part of the building is AC while the rest of it is NV possibly due to programmatic requirements such as conference rooms and computer labs or due to warm indoor conditions. In such zoned mixed mode (MM) buildings, occupants move frequently between the AC and NV zone which poses an interesting question - Does the experience of comfort in the AC zone influence the comfort expectation of occupants who primarily work in the NV zone? To answer this question, the physical environmental conditions, use of adaptive actions and thermal comfort responses need to be evaluated in both the zones of the MM building.

1.2. Objective

The objectives of this thesis can be classified into two main categories. First is to evaluate IEQ, adaptive action and thermal comfort for Alameda and Jaipur individually and the second is to do a comparative analysis between them. Specifically, the objectives are:

1) Compare the following IEQ parameters in the NV building in Alameda and the NV buildings in Jaipur:
   - Indoor temperature
   - Relative humidity
   - Carbon dioxide concentration
   - Air speed
2) Evaluate and compare behavioral adaptation in NV buildings in Alameda and Jaipur:
   - Clothing adjustment (identify parameters that influence clothing decisions)
   - Window adjustment (develop a mathematical model to predict window status)
   - Fan operation (develop a mathematical model to predict fan status)
3) Evaluate and compare thermal comfort in NV buildings in Alameda and Jaipur:
   - Thermal sensation relation with indoor/outdoor temperature
   - Comparison of comfort results with ASHRAE standard 55
   - Relationship between indoor comfort temperature and running mean outdoor temperature
   - Relationship between thermal sensation and thermal comfort/acceptability
4) Evaluate indoor environmental quality, adaptive actions and thermal comfort in the AC and NV zones of zoned type MM buildings in Jaipur

1.3. Significance

The work presented in this thesis is intended to bring forth the role of IEQ, occupant adaptation and thermal comfort in energy efficient building design, for both existing and new buildings. The existing buildings, especially those that rely primarily on AC for providing comfort will benefit greatly in saving energy and keeping occupants satisfied if they are retrofitted to provide adaptive opportunities and maintain appropriate levels of IEQ parameters as observed in the NV buildings in this thesis. On the other hand, for new buildings, the IEQ, comfort and adaptation results from the NV and MM buildings will act as precedents to look up to during the design phase.

In this thesis, new methods of data visualization are explored compared to the ones commonly used in other thermal comfort and adaptive action field studies to illustrate building performance, adaptive actions, occupant response and the relationship between them. This allows for an effective communication of the results and a better understanding of the data. A unique contribution of this study is the new statistical methods used to model window interaction in Alameda that allows for a more robust prediction of window status. The model also allows for quick interpretation of window interaction patterns with varying physical environmental conditions.

Although a growing number of new buildings are expected to be mixed-mode given the potential energy savings, there are very few studies that have evaluated the physical conditions and occupant feedback in a MM building. The results about comfort, adaptation and expectation in MM buildings presented in this thesis are intended to inform the design of new buildings.

Chapter 2: The field study

2.1. Alameda project

2.1.1. Building description

The case study building in Alameda is one of the few NV buildings in the bay area with both operable windows and ceiling fans (Figure 1). It is the office of an architecture and energy consulting firm, located on the second floor of the two-storied building. It is oriented Northeast Southwest and is glazed on three facades (15% overall window to wall ratio) with double pane glass except the Southwest. Automated sunshades regulate the visual comfort in the workspace. The construction material is light weight wooden frame and has insulation of approximately R-30 in the floor and ceiling and R-11 in the walls.

13 employees work in this two room office, each having a floor area of 1395 sf.; 7 of the 13 employees work in the front room while 6 of them work in the back room. The front room has higher internal gains compared to the back due to the printer, copier and server. Only the front room has ceiling fans (four of them) and a few people in both the rooms have personal fans. The office does not have central heating and is mostly heated by solar gain, internal loads and the five personal electric heaters; three in front and two in back room.

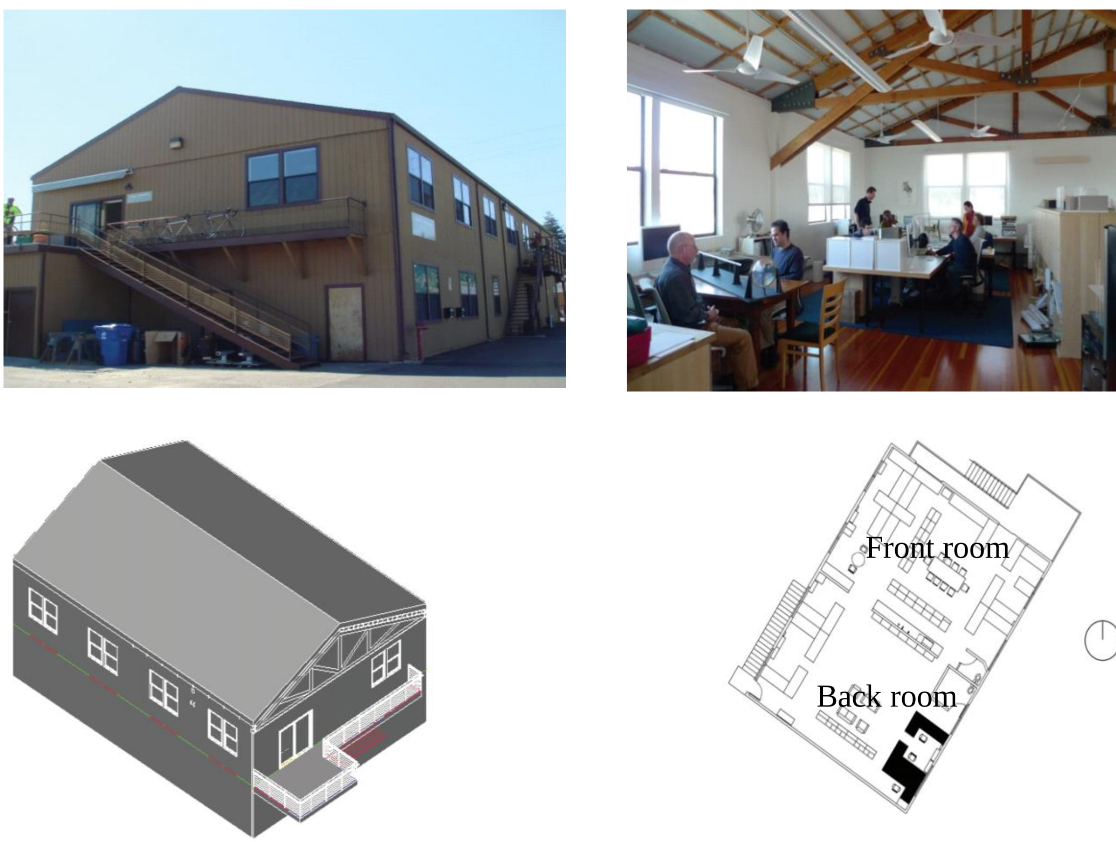

Figure 1. Photos and drawings of the Alameda case study building.

2.1.2. Design of experiment and instrumentation

Outdoor data monitoring

Two hobo data loggers were placed outside of the building to record temperature and relative humidity at 5 minute intervals from Oct 2011 to Oct 2012. An outdoor weather station was set up at the top of a 10m high structure right outside of the building (Figure 2). A wind speed potentiometer recorded wind velocity and direction every 5 minutes. Outdoor CO_2 levels were also recorded throughout the year.

Figure 2. Outdoor weather station.

Indoor Environment Monitoring

Onset U-12 hobo data loggers (Figure 3) were distributed in every workstation, recording temperature and relative humidity at five minute intervals. 10 were placed in the front room and 6 in the back room to monitor local variation within each room (Figure 5). Because of the automated sunshade and light weight construction, air temperature was assumed to be approximately equal to the operative temperature. CO_2 levels were recorded in both the front and back rooms with Telaire 7001 (Figure 4). The range and accuracy of the instruments is shown in Table 1. The settings of the four ceiling fans in the front room of the office were monitored via a voltage recorder. The settings of the personal fans were not recorded.

Figure 3. Temperature and humidity data logger (U-12 data logger).

Figure 4. Carbon dioxide sensor (Telaire 7001).

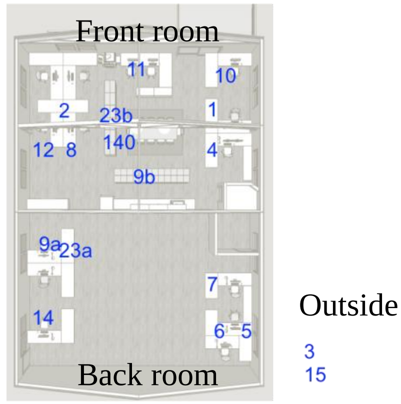

Figure 5. Placement of temperature sensors.

All windows were double hung type (Figure 6). To measure the window position, two digital cameras (Canon power shot A570) were mounted on a ceiling joist in the front room and two were mounted on a bookshelf in the back room such that all window positions were captured (Figure 7 and Figure 8). The camera's software was scripted to take pictures every 5 minutes (Konis 2011). These pictures were then read to determine window open percentage for each hour (Figure 6).

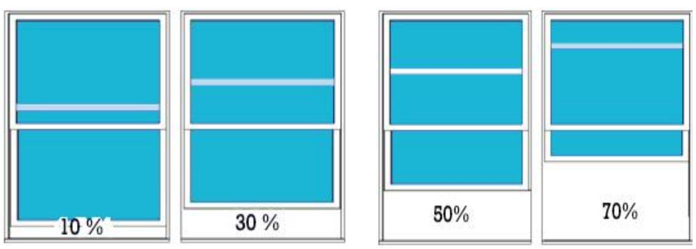

Figure 6. Window opening percentages.

Figure 7. Fish eye camera mounting.

Figure 8. Fish eye camera view.

Sr No.	Parameter	Instrument	Make	Range	Accuracy
1	Outdoor/ Indoor temperature	U-12	Onset	-20˚C to 70 ˚C	± 0.35 ˚C
2	Relative humidity	U-12	Onset	5% to 95%	± 2.5%
3	CO_2	Telaire 7001	Telaire systems	0 to 10,000 ppm	± 50 ppm

Table 1. Description of instruments used in Alameda study.

Occupant Survey

Alameda study was a longitudinal type study where the occupants answered a custom "right now" survey 2 weeks per month between October 2011 and October 2012 (Appendix a). The survey was administered online, three times a day and 1408 responses were collected in total. They were asked about thermal comfort (sensation, acceptability, and preference) as well as air movement, air quality, noise, and clothing. The survey had a continuous scale which was then converted to discrete for analysis. Thermal sensation responses were converted to the 7-point ASHRAE scale from -3 (cold), 0 (neutral) to 3 (hot). The responses to questions about thermal, air movement, and air quality acceptability were also converted to a 7-point scale from -3 (not at all acceptable) to 3 (very acceptable).

2.1.3. Climate

Hourly values of temperature, humidity and wind are shown with a heat map (Figure 10, Figure 11 and Figure 12). The x axis is the month while the y axis is the hour of the day. The color gradient represents the intensity of the variable.

Alameda is a mild climate with cool winters and slightly warm summers. Summer season is from June – October where the mean monthly outdoor temperature is above 17 ˚C with a maximum of 32 ˚C (Figure 10). Winter is from December – February where the mean outdoor temperature is below 11 ˚C (Figure 10). In between these two seasons there are few transition months (swing season) from March – May and in November where the mean monthly temperature is between 11 – 17 ˚C (Figure 10). The mean outdoor temperature during occupied hours (7 am – 8 pm) in the summer is 20 ˚C, in winter is 11 ˚C and in swing is 15.6 ˚C. The mean outdoor temperature during late evening and night hours (8 pm – 6 am) in summer is 15.6 ˚C, winter is 7.7 ˚C and swing is 11˚C. Throughout the year, there are very few hours when the outdoor temperature is warm (above 27 ˚C) and whenever the outdoors gets warm, it is mostly during the afternoons (dotted region in Figure 10). Outdoor humidity level during both summer and winter is 69% which is surprisingly high (Figure 11).

Mean outdoor air speed during all three seasons is around 2 m/s. High winds (3 – 6 m/s) blow during late afternoon and evening from May – September (dotted region in Figure 12). This is the time when outdoor temperature is in the mid-twenties (Figure 10) and occupants can make the best use of air movement to keep themselves comfortable. High wind speeds predominantly prevail from the Northeast direction (Figure 13).

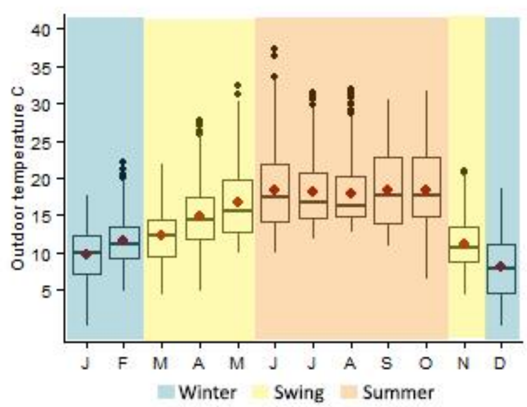

Figure 9. Monthly outdoor temperature in Alameda.

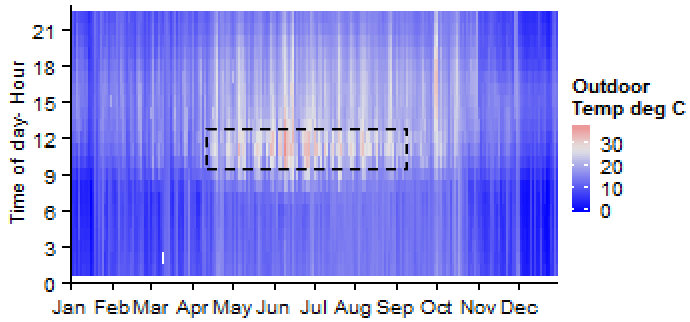

Figure 10. Hourly outdoor temperature in Alameda.

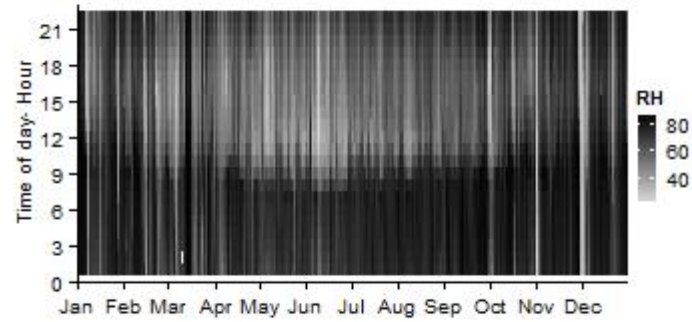

Figure 11. Hourly outdoor RH in Alameda.

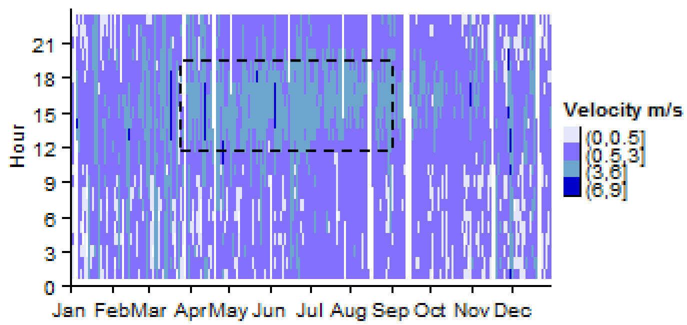

Figure 12. Hourly outdoor wind speed in Alameda.

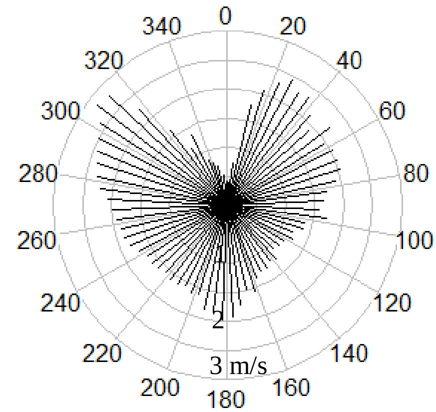

Figure 13. Wind speed averaged every 5 deg- Alameda.

2.2. Jaipur project

2.2.1. Building description

36 buildings were surveyed and monitored in total; 6 were purely AC, 17 purely NV, 2 concurrent type MM and 11 zoned type MM. In this thesis, data from only the 17 purely NV buildings and 11 zoned type MM buildings is analyzed. The data from the 6 purely AC buildings is evaluated only for the comparison of CO_2 concentration.

The NV and MM buildings included academic and commercial offices and dormitories (Figure 14 and Figure 15). Occupants in all these buildings did desk based work. In total, 1373 votes were collected from purely NV buildings and 560 from MM buildings. Amongst the 560 MM votes, 274 were from the NV zone and 286 from the AC zones.

Typically, the construction material was 200mm brick with 200mm of cement plaster on both sides. In some buildings, the bricks were left exposed while in some they were covered with locally available stone material (Figure 16). In 95% of the buildings, windows had single pane clear glass. These buildings did not have central heating, but some occupants used personal heaters. Unlike the Alameda building, the Jaipur ones did not have high internal heat gain from equipment.

Figure 14. Exterior view of NV buildings.

Figure 15. Exterior view of a MM building.

Figure 16. Brick wall coated with stone.

2.2.2. Design of experiment and instrumentation

The Jaipur project was a transverse study conducted across 36 buildings from April 2011 to July 2013. Occupants were surveyed between 9 am – 6pm. They were asked about their "right-now" opinion of the temperature, humidity and air movement in their ambient surrounding (Appendix b). The survey also asked the occupants to rate their comfort opinion (very uncomfortable – very comfortable) in addition to thermal sensation (cold – hot). The survey was paper based and while the occupants answered the questions, the surveyor noted down the window, fan, blind and door status in the immediate vicinity of the occupant (Figure 17). A movable stand mounted with temperature (air and globe), humidity, air velocity and CO_2 sensor monitored the physical conditions close to the occupant (Figure 18). The range and accuracy of the instruments used is shown in (Table 2).

Figure 17. A surveyor noting environmental conditions while the occupant fills out the survey.

Figure 18. Location of taking physical measurements.

Fig. No.	Parameter	Instrument	Make	Range	Accuracy
Figure 19 (a)	Globe temperature (Diameter- 150 mm)	480 VAC	Testo	0 – 120 ºC	± 0.5 ºC
Figure 19 (b) and (e)	Air velocity	480 VAC	Testo	0 – 50 ºC 0 – 5 m/s	± 0.5 ºC ± 0.03 m/s
Figure 19 (c)	Air temperature and RH	480 VAC	Testo	-20 – 70 ºC 0 – 100 % RH	± 0.5 ºC ± 1%
Figure 19 (d)	-	Logger	Testo	-	-
Figure 19 (f)	CO2	435-2	Testo	0-10000 ppm	± 50 ppm
-	Outdoor temperature	Weather station	Virtual instrumentation	-40-123.8ºC	± 0.5 ºC

Table 2. Description of instruments used in Jaipur study.

Figure 19. Instruments used in Jaipur study.

2.2.3. Climate

Jaipur is a semi-arid climate. Summer months are from April – October where the mean monthly outdoor temperatures are above 28 ˚C. Winter is from November to March (Figure 20) where the mean monthly outdoor temperature is less than 27 ˚C. Monsoon season occurs in the middle of summer season between mid-July and mid-September. The monsoon season can be identified from the humidity chart shown in Figure 22; there is a dark black patch showing high humidity from July to August. Since the difference between the mean outdoor temperature during monsoon and summer is almost the same (3K difference), the two monsoon months are merged with summer. The mean outdoor temperature during occupied hours (7 am – 8 pm) in summer is 32 ˚C and goes to a maximum of 44 ˚C. During late evening and night hours (8 pm – 6 am) the mean outdoor temperature is 28 ˚C.

Excluding the monsoon months, the mean value of humidity in summer is 34%. During monsoon the mean outdoor temperature during occupied hours is 29 ˚C and mean RH level is 78% during occupied hours. In winter, the mean outdoor temperature during occupied hours is 20 ˚C, which is significantly lower than summer. The mean RH during winter is 41%.

The mean outdoor air speed during summer is 4.3 m/s and during winter is 3 m/s. The weather station was mounted within 3 mile of the surveyed buildings and so the air speed values are fairly close to the outdoor air speeds prevailing near the building. An air speed of 4.3 m/s shows a promising potential for having natural ventilation during summer. Moreover, the high wind speeds are observed during the warm occupied hours from May- July; dotted region in Figure 23. High winds predominantly blow from the East and Northeast (Figure 24).

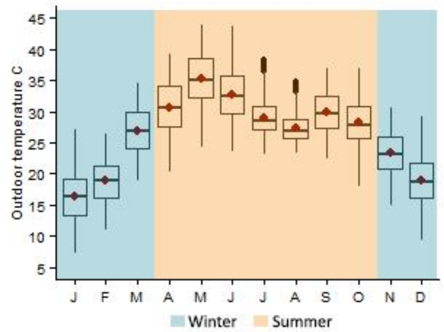

Figure 20. Monthly outdoor temperature in Jaipur.

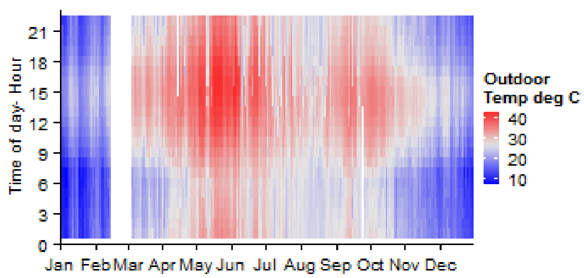

Figure 21. Hourly outdoor temperature in Jaipur.

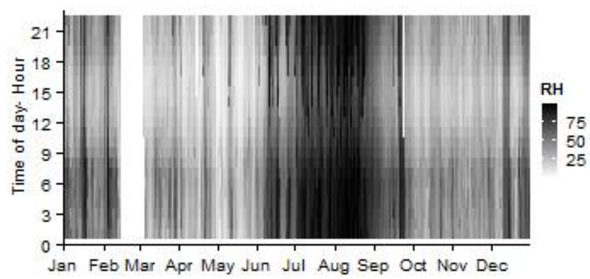

Figure 22. Hourly outdoor RH in Jaipur.

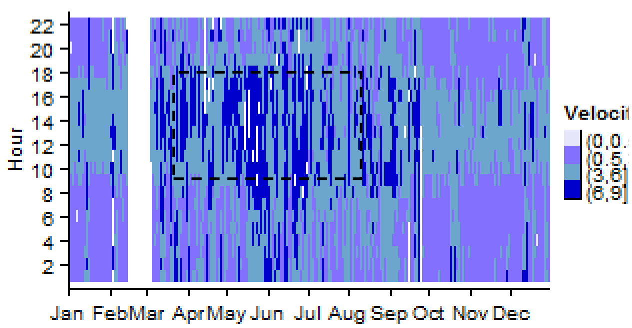

Figure 23. Hourly outdoor wind speed in Jaipur.

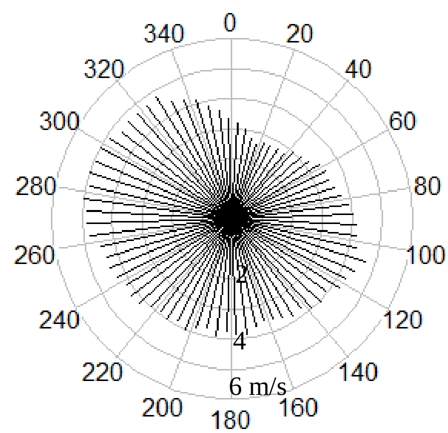

Figure 24. Wind speed averaged every 5 deg in Jaipur.

2.3. Summary of climatic variables from Alameda and Jaipur

Table 3 summarizes the mean values of outdoor temperature, relative humidity and wind speed in Alameda and Jaipur. The summers in Jaipur are much warmer than Alameda; the mean outdoor temperature is 9 ˚C higher than Alameda. However, Jaipur has much higher wind speed than Alameda during summer; 4.3 m/s compared to 2 m/s. The outdoor humidity during summer in Jaipur is higher than Alameda, possibly because of the inclusion of the monsoon months. During winter, Alameda is much cooler than Jaipur with a mean outdoor temperature of 11 ˚C compared to 20 ˚C. The mean wind speed in Jaipur is 1 m/s higher than Alameda during winter while the RH around 30% lower.

Variable	**Season**	**Alameda**	**Jaipur**
Mean outdoor temperature ˚C	Summer	20	29
	Winter	11	20
Mean relative humidity (%)	Summer	69	78
	Winter	69	41
Mean wind speed (m/s)	Summer	2	4.3
	Winter	2	3

Table 3. Comparison of climatic variables from Alameda to Jaipur.

Chapter 3: Indoor environmental quality in NV buildings

3.1. Introduction

Indoor environmental quality (IEQ) is a key factor in occupant satisfaction and building performance as occupants spend up to 90% of their time indoors consciously/sub-consciously experiencing the indoor environment. IEQ studies in NV and MM buildings generally fall in two categories, those relating to thermal comfort – temperature, humidity and air speed and those relating to indoor air quality- ventilation rate and carbon dioxide (CO_2) concentration. It is important to evaluate these IEQ parameters as they significantly contribute towards better work performance, productivity and health (Kosonen and Tan 2004).

Indoor temperature conditions in NV buildings have been found to be in a wider range than air conditioned buildings. During winter, in mild and cold climates the indoor conditions in NV buildings are maintained at a comfortable level either by central heating, personal heaters, internal and solar heat gain. In mechanically ventilated buildings in a cold climate like Montreal, the indoor temperature went lowest till 22 ˚C during winter (Donnini 1996). During summer especially in hot climates such as Thailand, Bangkok and Hyderabad, indoor temperatures in NV buildings have been found in the range of 27 – 38 ˚C (Busch 1992, de Dear 1991, Feriadi and Wong 2004, Indraganti 2010). Occupants are comfortable in these higher temperature and the relationship between temperature and comfort is further elaborated later in the thermal comfort chapter.

In warm climates, although one might expect cooler indoor temperatures in air conditioned buildings to keep people comfortable, they often run a risk of overcooling and making people uncomfortable (Mendell and Mirer 2009). deDear and Leow studied 12 AC buildings in Singapore and found that one third occupants complained to be thermally dissatisfied because the zones were overcooled. The mean indoor temperature in these AC buildings was 23 ˚C (de Dear 1991). Similar result was found in another study done in 61 AC buildings in Hong Kong; 186 out of 422 respondent complained of thermal discomfort due to cool indoors (Mui and Wong 2007).

The challenge of coping with high temperature and humidity can often be efficiently met by use of elevated air movement. It is the key factor that provides comfort at high indoor temperatures in the tropics (Nicol 2004). de Dear and Leow found indoor air speed to be in the range of 0.22 – 0.58 m/s in four naturally ventilated buildings in Singapore (de Dear 1991). In a study done in residential buildings in Bangladesh, subjects voted to be comfortable in the temperature range of 24 – 33 ˚C and high humidity. Ceiling fans were widely used and the indoor air speed ranged between 0.15 to 0.45 m/s (Mallick 1996). Evaluating whether air movement is desired in hot climates, a study by Candido et.al in Brazil found that the percentage of people wanting no change in air speed increased linearly when the air speed increased from 0.5 to 0.9 m/s. People desired air speed as high as 0.9 m/s when the indoor temperature reached 30 ˚C (Cândido et al., 2010).

Interestingly in hot climates, air movement is preferred not only in NV buildings but also in AC buildings. The RP 702 study in 12 AC buildings in Townsville found that thermal discomfort was associated with the want for higher air velocity (de Dear and Fountain 1994). This might be very likely because occupants spend a significant amount of time in naturally ventilated spaces that have high air movement and a good air change rate. Thus the expectation of IEQ could be associated with the conditions which prevail outdoors or at home where air conditioning is absent.

An important aspect of IEQ is indoor air quality (IAQ) and it has a high stake on occupant health and productivity. However, determining a metric for work performance, productivity and health is challenging. Some commonly used metrics in experiments are short term sick leave, task based performance such as solving math, typing or answering phone calls in a call center and self-reported productivity (Wargocki 2000). Short term sick leave, assumed to be triggered by indoor generated air borne pollutants, decreased on increasing the ventilation rate (Seppänen and Fisk 2006). In a study involving 90 subjects, Wargocki et.al found that the performance of office tasks (typing, addition and proof reading) increased by 1.9% for each two-fold increase in the ventilation rate; the pollution load was held constant (Wargocki 2000). Accounting for energy cost involved in increasing the ventilation rate and other economic factors, a rough estimate of the potential monetary annual savings and productivity gains in the US is in the range of $30 billion to $170 billion (Fisk and Rosenfeld 1997).

The following points can concluded from the literature review:

- In mild climates, comfortable indoor temperatures in winter are maintained by central heating, personal heater, internal and solar heat gain.
- In hot climates, the indoor temperature range in NV buildings is typically between 27- 38 ˚C.
- Air conditioned buildings in hot climates run a risk of overcooling and making occupants uncomfortable.
- Air speed in NV buildings in hot climates range from 0.15 – 0.9 m/s.

3.2. Analysis method

“There is a magic in graphs. The profile of a curve reveals in a flash a whole situation — the life history of an epidemic, a panic, or an era of prosperity. The curve informs the mind, awakens the imagination, convinces.”- Henry D Hubbard, 1939

Visual representations are an effective way of communicating results from large datasets. Multiple layers of information can be overlaid on a graphic allowing the viewer to explore the interrelationship between different trends. Edward Tufte, a noted pioneer in the field of data visualization refers to it as ‘escaping flatlands’ (Tufte 1983). He elaborates this point further with a map shown in Figure 25. According to him, this map by Charles Joseph Minard is the most effective graphic illustration ever made. The map illustrates the losses suffered by Napolean’s army during his invasion of Russia in 1812. The diminishing thickness of the cream colored band from the left shows the loss of Napolean’s army as they approached Moscow (Figure 25). The black line which goes from right to left shows Napolean’s retreat. The names of the locations where the battles took place are also overlaid on the graph. These are tied to the temperature and time scales below. In total, 6 variables are displayed in a single graphic (Tufte's website).

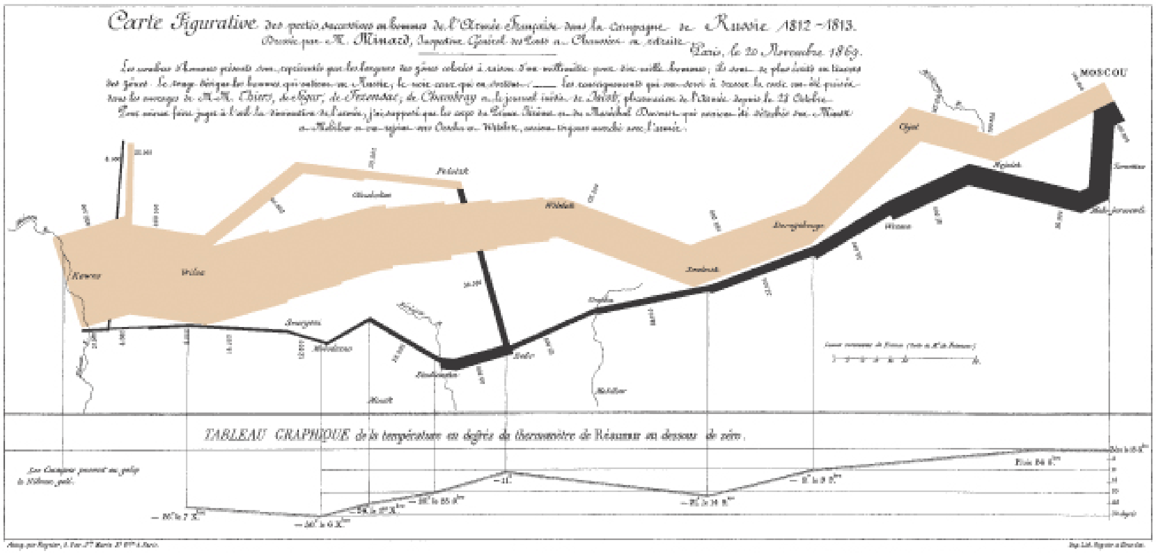

Figure 25. A map of Napolean's march to Moscow during the war of 1812. Source: Edward Tufte's website.

In this thesis, the principles of data visualization have been extensively used for representing building performance, adaptive action and thermal comfort results wherever relevant. Each graphic aims to answer a specific research question. Each graph is meant to answer a specific research question. For instance a question could be – "What humidity sensation do occupants have at high indoor temperature and humidity?" Figure 26 shows the humidity sensation (as color) for different indoor temperature and humidity. When the indoor temperature is above 29 ˚C and RH is above 70% (region above the horizontal dotted line and to the right of the vertical dotted line), there are very few red dots which means occupants don't feel moderately/ very humid. Follow-up questions such as "What is the air speed in the hot-humid conditions?" are also evaluated using data visualization methods. Statistical significance is calculated wherever relevant.

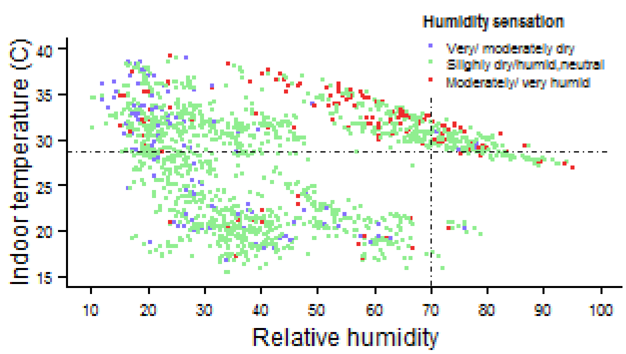

Figure 26. Example of data visualization technique.

3.3. Results

3.3.1. Temperature

Figure 27 shows the distribution of indoor temperature for Alameda and Jaipur. Overall, indoor temperature in the Alameda building is much cooler than the Jaipur buildings, with an overall mean of 23 ˚C compared to 27 ˚C (Figure 27). During summer in the Alameda building, the indoor temperature ranges between 20 to 28 ˚C with a mean of 25 ˚C, while in the summers of Jaipur, indoor temperatures is between 20 ˚C to 39 ˚C with a mean of 30 ˚C (Figure 27). During the winter in Alameda (December- February), the indoor temperature is between 14 – 28 ˚C with a mean of 21 ˚C. Interestingly, indoor temperature during winter in Jaipur is also in a similar range (14 to 33 ˚C) with a mean of 24 ˚C.

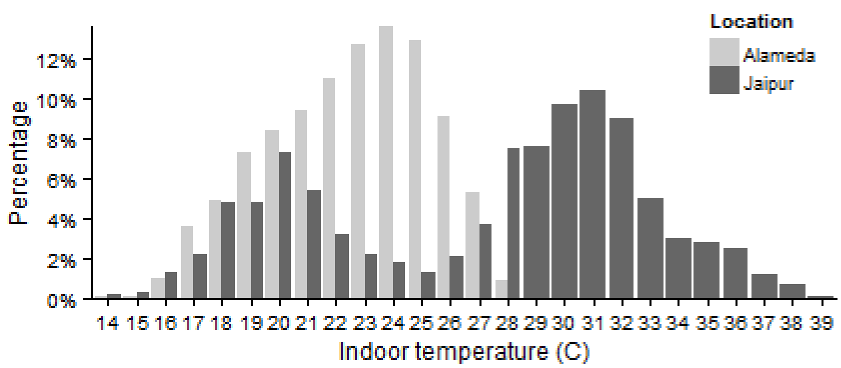

Figure 27. Indoor temperature distribution.

Figure 28 shows patterns of simultaneous indoor and outdoor temperature in both the climates. Indoor temperature in the Alameda building is warmer than outdoors in 95 % of the observations. Although the indoor temperature in Alameda was recorded continuously for one year at 5 minute interval, for comparison purposes to Jaipur, only those observations are shown when occupants answered the survey. During summer, the indoor is around 5 ˚C warmer than outdoors while in winter it is 9 ˚C (mean value) (Figure 28). On the other hand, Jaipur indoor temperatures are cooler than outdoors in 85 % of the observations; 5 ˚C in summer and 2 ˚C in winter (mean value).

Another interesting thing to note is that the indoor temperature in Alameda is much warmer than Jaipur in the overlapping region (15 – 25 ˚C) of outdoor temperature. The difference in indoor temperature is very likely because the Alameda building had insulation and internal heat gain while the Jaipur buildings typically did not have either of them.

The Alameda study asked the question- “Right-now how acceptable is the temperature at your workplace?” and the Jaipur study asked- “Based on temperature, humidity and air movement how comfortable do you feel right now in your workplace?” Figure 29 and Figure 30 shows the ‘acceptability vote’ distribution in Alameda and ‘comfort vote’ distribution in Jaipur with indoor and outdoor temperature. Overall, occupants voted to be acceptable of the temperature in 98% of the observation in Alameda while 86% voted to be comfortable in Jaipur. Assuming indoor temperatures above 29 ˚C to be representative of warm conditions (shown by a horizontal dotted line in Figure 30), it is interesting to note that occupants voted to be comfortable in 80% of the observations when the indoors were above 29 ˚C in Jaipur (Figure 30).The relationship between temperature and occupant satisfaction is elaborated further in the thermal comfort chapter (6).

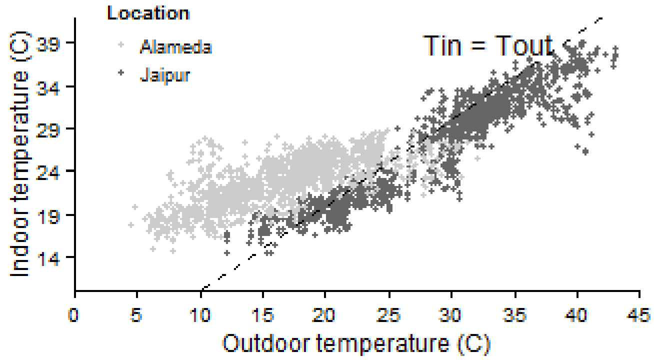

Figure 28. Indoor - outdoor temperature.

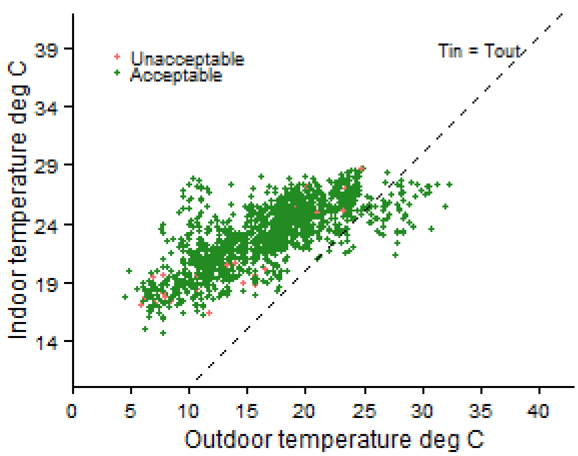

Figure 29. Acceptability vote distribution with indoor and outdoor temperature in Alameda.

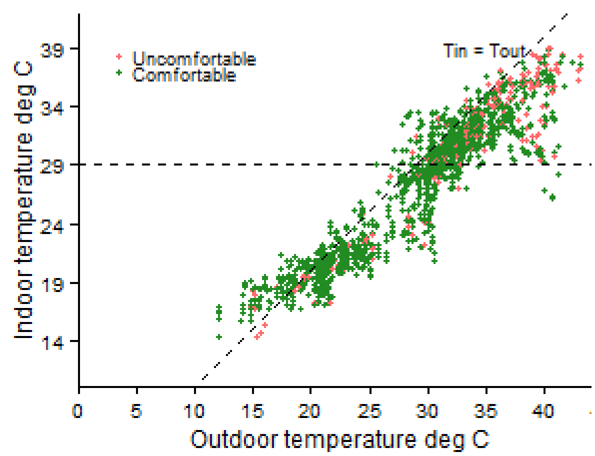

Figure 30. Comfortable vote distribution with indoor and outdoor temperature in Jaipur.

3.3.2. Relative humidity

Relative humidity (RH) in the Alameda building is lower and tightly distributed as compared to Jaipur (Figure 31). The indoor RH never goes above 54% in Alameda while it goes above 60% in 40 % of the observations in Jaipur (Figure 31). During summer, the indoor RH level in Alameda ranges between 30 - 50% (mean = 42 %) while in Jaipur, it is between 27 - 95% (mean = 43%). Jaipur indoors are dry for majority of the year except for the monsoon months from July – September (Figure 32).

The humidity level needs to be carefully evaluated in order to understand its implications. The Jaipur study asked a question about humidity sensation- “On the basis of humidity, how do you feel right now?” The options were on a 7 point scale ranging from “very dry” to “very humid”. Figure 33 shows the humidity sensation distribution from Jaipur. Overall, 82% of the occupants in Jaipur voted in the middle three categories, that they felt either “slightly dry”, “neutral” or “slightly humid”. This forgiving humidity could be because of two reasons: occupants are not sensitive to humidity especially when in sedentary position (Fountain 1999). Another possibility is that there is air movement which is helping in increasing the body heat loss and making the humidity less noticeable.

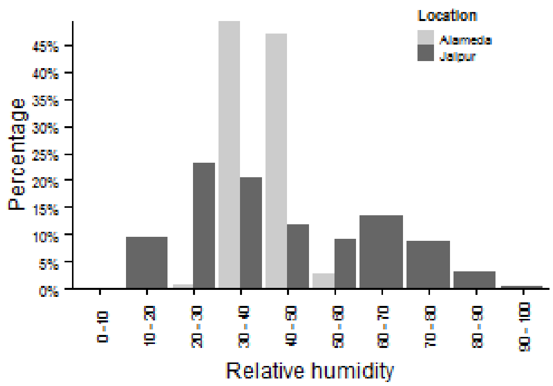

Figure 31. Indoor RH in Alameda and Jaipur.

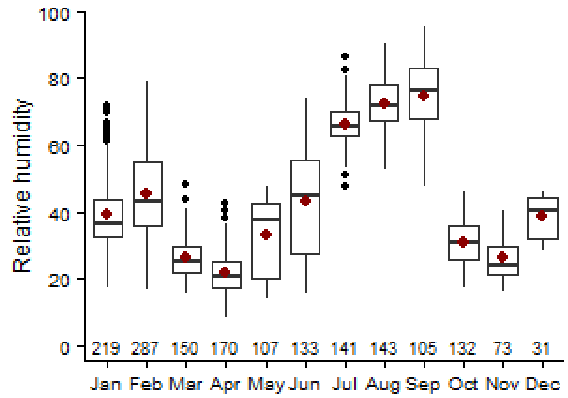

Figure 32. Monthly indoor RH in Jaipur.

In the Jaipur study, 118 observations had humidity level greater than 70% when indoor temperature was above 29 ˚C (Figure 35). For illustrative purposes, this temperature and humidity range is assumed to be emblematic of hot-humid conditions. Even in these conditions, 78% of the occupants voted their humidity sensation to be between “slightly dry”, “neutral” or “slightly humid” (Figure 34). The mean air speed for this range of RH and temperature is 0.8 m/s. This result shows that occupants adapted themselves to the wide range of humidity conditions in a hot climate possibly by having elevated air movement.

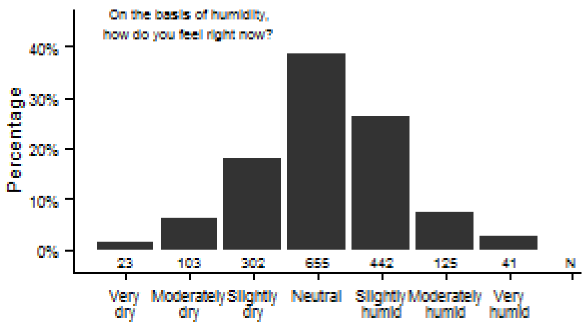

Figure 33. Humidity sensation recorded in Jaipur (All observations included).

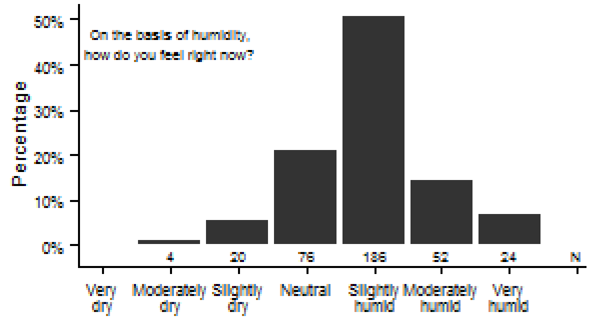

Figure 34. Humidity sensation when indoor temperature is greater than 27 ˚C and RH above 60%.

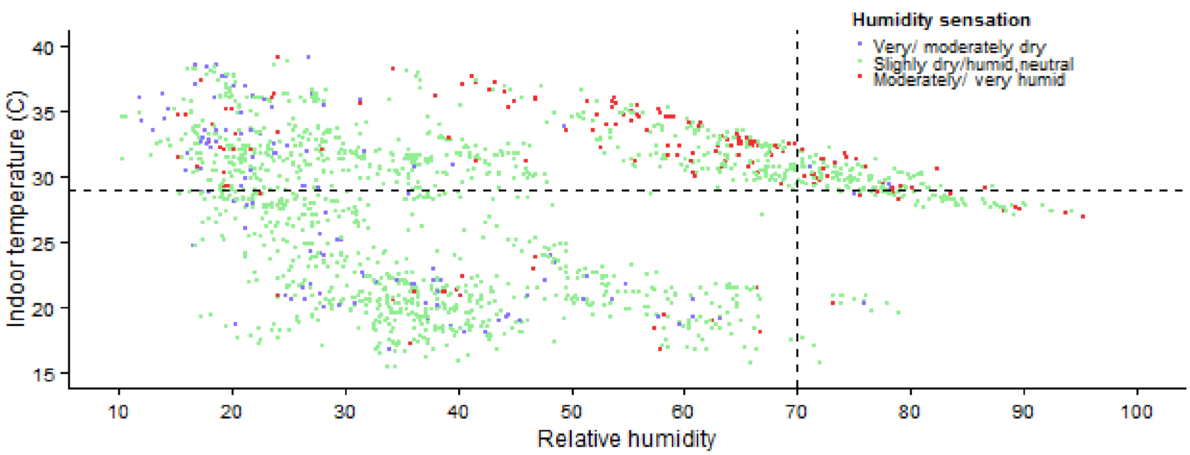

Figure 35. Humidity sensation at different indoor temperature and RH in Jaipur.

Location	Season	N	min	1st Q	Median	mean	3rd Q	Max	SD
Alameda	Annual	1408	26.52	38.09	39.98	40.62	43.12	54.04	4.18
	Summer	522	30.87	39.44	41.68	42.49	45.34	54.04	4.5
	Winter	451	28.94	37.7	39.74	39.87	42.56	47.37	3.46
	Swing	435	26.52	37.3	39	39.14	41.03	50.22	3.6
Jaipur	Annual	1691	8.48	26.66	38.1	43.25	60.7	95.28	19.74
	Summer	931	8.48	26.95	35.13	42.92	60.64	95.28	20.29
	Winter	760	13.7	24.58	34.38	36.92	41.85	89.2	16.52

Table 4. Summary of indoor relative humidity in Alameda and Jaipur.

3.3.3. Air speed

In naturally ventilated buildings, air movement is a key factor that influences comfort. It also allows opportunities for providing cost effective comfort solutions using operable windows and ceiling fans. Although indoor air speed data is very valuable in a field study, data logging is constrained by duration of study and expensive instrumentation. The Alameda project being a year-long longitudinal study did not monitor indoor air speed while the Jaipur project, which is a transverse study did record air speed. Thus the results presented in this section are only from the NV buildings in Jaipur.

The air speed in Jaipur is within the range of 0.2 – 1.2 m/s in 77 % of the observations (1136 out of 1470) and above 1.2 m/s in 12% of the observations (180 out of 1470) (Figure 36). 1.2 m/s is the threshold limit specified by ASHRAE for air speed inside a building if there is local control (2013). One of the argument against having high indoor air speed is that it might cause discomfort due to draft (especially for cool temperatures) or inconvenience due to papers blowing away. This would imply that when air speed is greater than 1.2 m/s, occupants would prefer to have lower air speeds. Figure 37 shows the air velocity preference mapped on to the bin of air speed. Overall, occupants prefer no change or more air movement in 84% of the observations. When the air speed is between 1.2 – 3 m/s, 30% occupants want to have no change in air speed and 58% want to have more air movement. Thus the argument that occupants prefer to have lower air movement at higher air speed does not hold true. In fact, this shows an aspect of behavioral adaptation where occupants have overcome the possible discomfort and inconvenience issues of air movement.

The temperature and humidity conditions under which air speed varies is also interesting as shown in Figure 38. For illustrative purposes, indoor temperature above 29 ˚C is assumed to be warm and RH above 70% is assumed to be humid. When indoor temperature is greater than 29 ˚C, air speed is greater than 0.5 m/s in 65% of the observations. When RH is greater than 70%, air speed is greater than 0.5 m/s in 48% of the observations. When indoor temperature is greater than 29 ˚C and RH is greater than 70%, air speed is greater than 0.5 m/s in 65% of the observations (Figure 38). This result is in agreement with the findings from other studies done in hot climates where the high indoor temperature and humidity conditions are accompanied with high air velocities (Nicol, 2004, Mallick, 1996, Cândido et al., 2010, Indraganti, 2010).

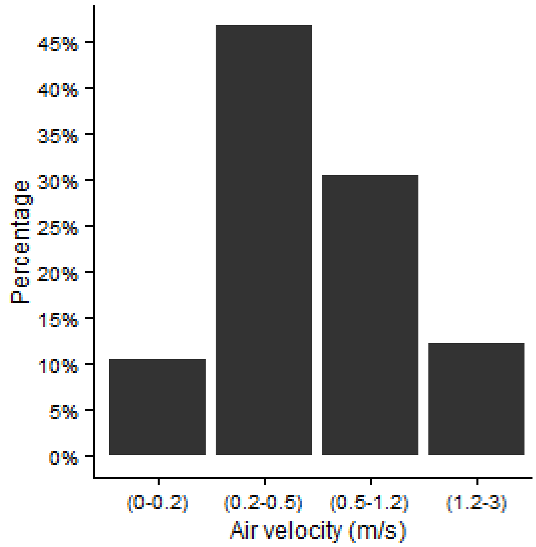

Figure 36. Indoor air speed in NV buildings in Jaipur.

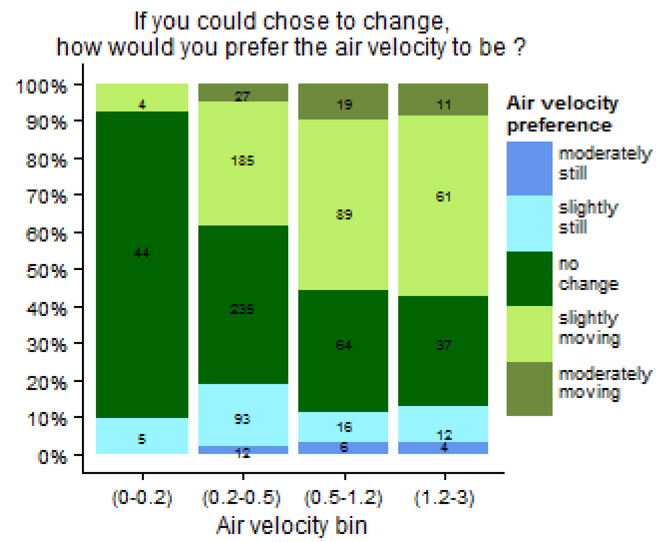

Figure 37. Air velocity preference in Jaipur.

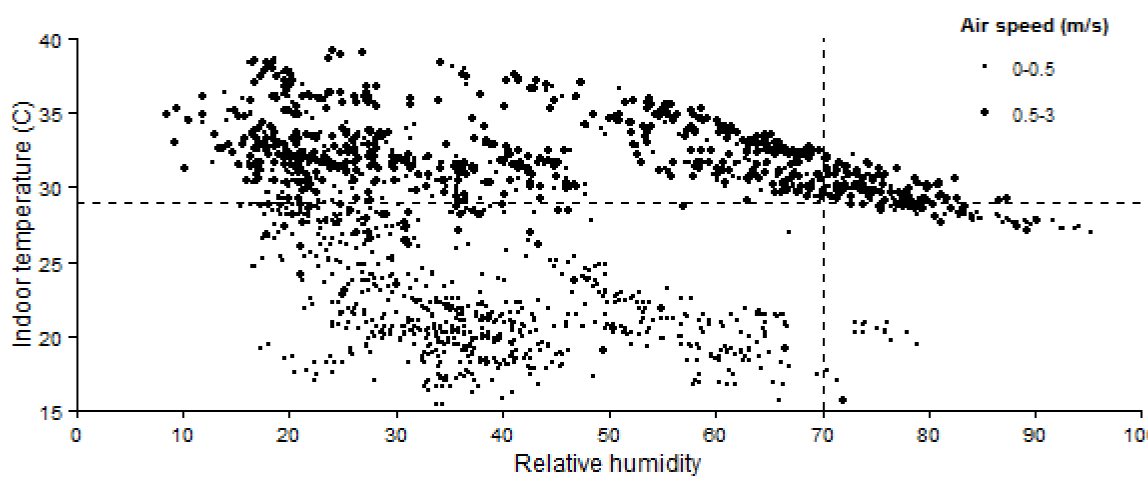

Figure 38. Air speed at different indoor temperature and humidity.

Interestingly, when the indoor temperature is less than or equal to 29 ˚C and the RH is less than or equal to 70%, the air speed is less than 0.5 m/s in 95% of the observations. This shows that the air speed in these buildings is controlled by the occupants possibly by operating windows and fans. To evaluate the influence of windows and fans on air movement, Figure 39 and Figure 40 show the window and fan status at different indoor temperature and RH. When the indoor temperature is greater than 29 ˚C and the RH is above 70%; windows are open in 75% of the observation (n=28) while fans are on in 99% of the observations (n=118) (Figure 39 and Figure 40). The number of observations available for windows is much less than that for fans and moreover, when the windows are open, fans are on in 95 % of the observations. During the conditions of low air speed i.e. when the indoor temperature is less than 29 ˚C and the RH is less than 70%, fans are off in 74% of the observations (n=324). This illustrates that the air movement in these buildings is controlled mainly by the fans.

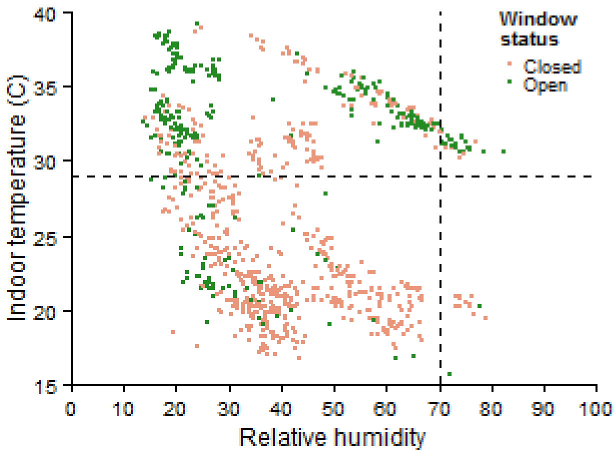

Figure 39. Window status at different indoor temperature and relative humidity.

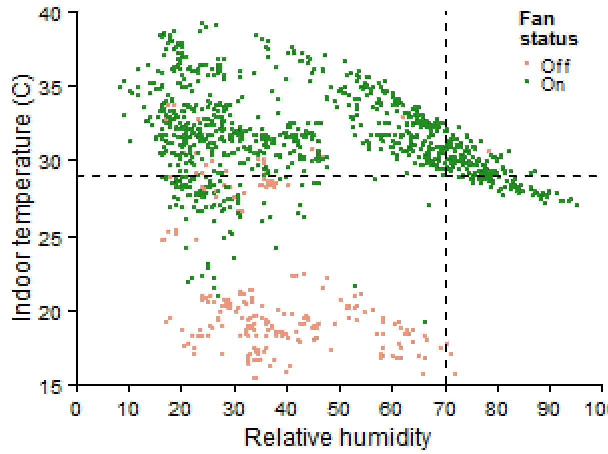

Figure 40. Fan status at different indoor temperature and relative humidity.

3.3.4. Carbon dioxide (CO_2)

Indoor air quality is an important metric while evaluating building performance. Carbon dioxide (CO_2), carbon monoxide, smoke, radon, molds, volatile organic compounds, asbestos fiber, bacteria and Ozone are some common indoor air pollutants (Wikipedia 2014). Amongst these pollutants, CO_2 has been found to influence occupant's acceptability of the space with regards to odor and is also a good proxy for estimating ventilation inside the building (Persily 1996). The indoor CO_2 distribution is similar in Alameda and Jaipur (Figure 41). In Alameda 82% of the observations had indoor CO_2 less than 600 ppm while in Jaipur it was 73%. The annual mean values of indoor CO_2 in Alameda is lower than Jaipur (528.15 ppm and 538 ppm respectively) (Table 5). Both these levels are well below the level of 1000 ppm where significant differences start appearing in an occupant's decision making ability (Satish et.al. 2012). The CO_2 concentration in purely AC buildings in Jaipur is way above the 1000 ppm value with a mean of 2249 ppm and a maximum value of 8400 ppm (N=594) (Figure 42). This clearly shows that AC buildings are not well ventilated.

One of the hypothesis of operable windows is that they bring in fresh outdoor air and help in maintaining acceptable CO_2 levels. To evaluate this hypothesis, CO_2 levels in both the climates are compared with windows open and windows closed during the summer months.

Figure 43 and Figure 44 show the CO_2 levels during summer work hours (7am – 8pm) and excluding weekends) for the front and back room respectively in the Alameda building. Windows remain closed, for 60% of the observations (1788 out of 2993) in the front and 68% of the observations (1399 out of 2058) in the back room. In both the rooms, the CO_2 level recorded at the times when the window was closed is significantly higher compared to the times when at least one window is open ($p<0.001$) (Figure 43, Figure 44).

A similar result is observed in Jaipur; CO_2 concentration is higher when the windows are closed as compared to when they are open ($p<0.001$) (Figure 45). Windows were closed in 39% of the observations (157 out of 400) during summer. Evaluating further the relationship between window status and CO_2 concentration, Figure 46 shows the CO_2 variation with outdoor temperature during the summer where the color of the dot indicates window status. When the outdoor temperature is above 37 ˚C, windows are closed and the CO_2 level goes above 700 ppm. This result validates the hypothesis that operable windows help in ventilating the building and maintaining acceptable CO_2 levels.

Location	**Season**	**N**	**Min**	**1st Q**	**Median**	**mean**	**3rd Q**	**Max**	**SD**
Alameda-Front room	Annual	2568	362	410	440	487.3	497	2499	135.472
	Summer and Swing	2353	362	408	434	470.2	478	1201	110.755
	Winter	215	426	507	631	674.1	807	2499	216.914
Alameda-back room	Annual	2604	68	475	510	569	597	1361	150.217
	Summer and Swing	2389	156	473	505	552.7	571	1361	133.087
	Winter	215	68	587	718	749.9	914.5	1234	202.434
Jaipur	Annual	1389	147	449	511	538.4	610	1456	174.928
	Summer	646	339	481.2	527	653.7	634	2359	356.588
	Winter	743	147	482.2	545	571.2	653	1057	128.959

Table 5. CO_2 concentration in Alameda and Jaipur buildings.

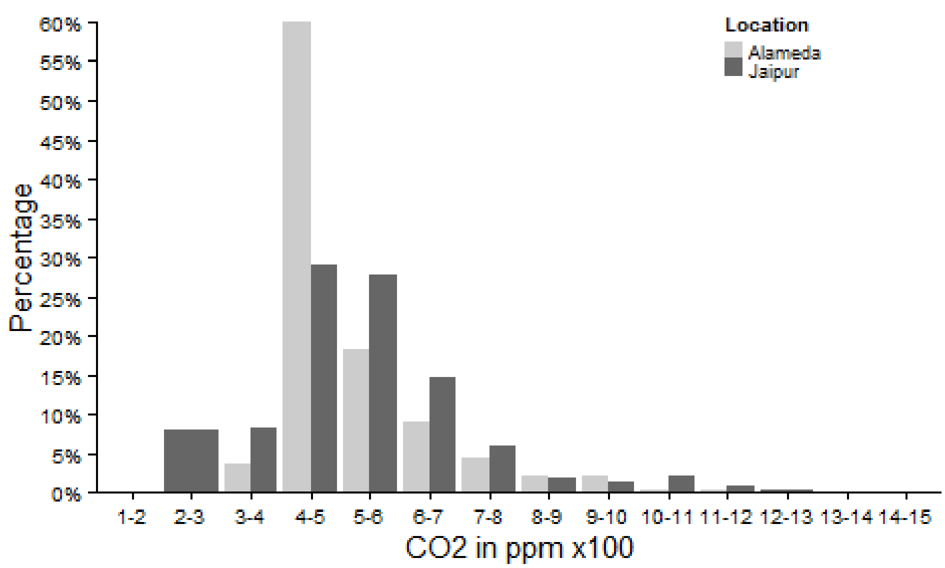

Figure 41. CO_2 concentration distribution in NV buildings.

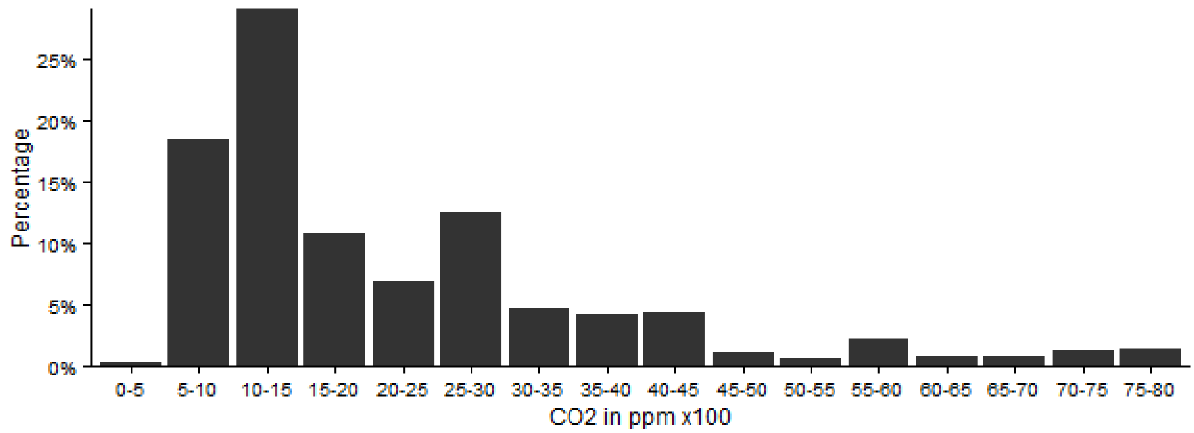

Figure 42. CO_2 concentration distribution in AC buildings in Jaipur.

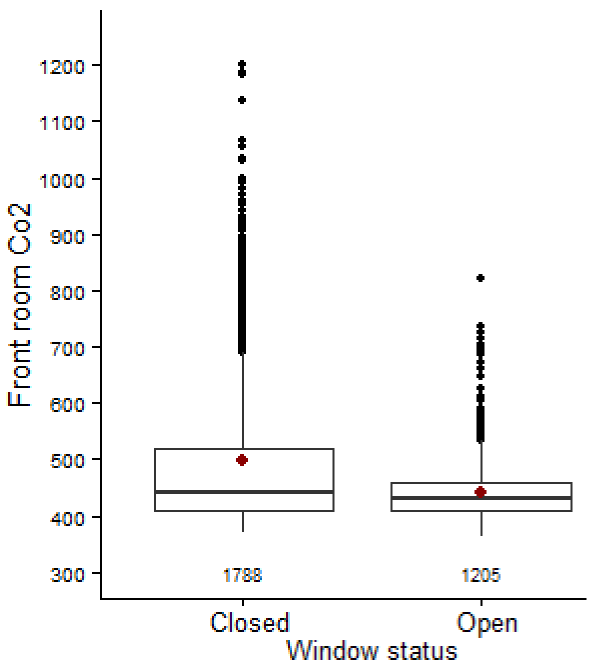

Figure 43. Indoor CO_2 concentration vs. window status in the front room during summer in the Alameda building.

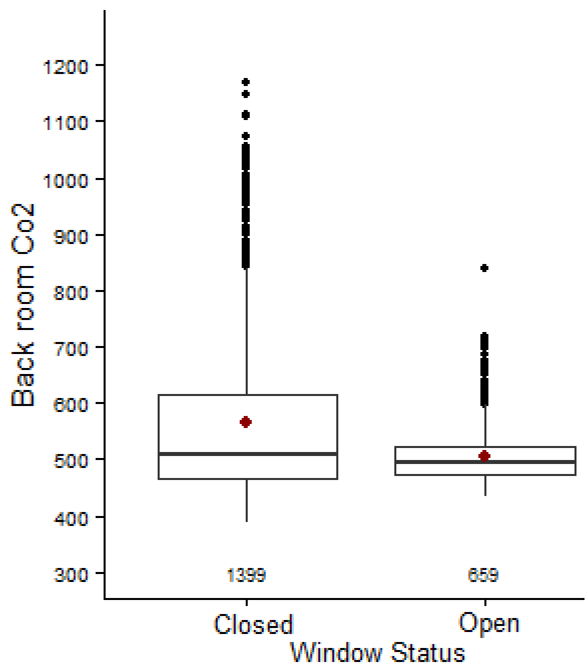

Figure 44. Indoor CO_2 concentration vs. window status in the back room during summer in the Alameda building.

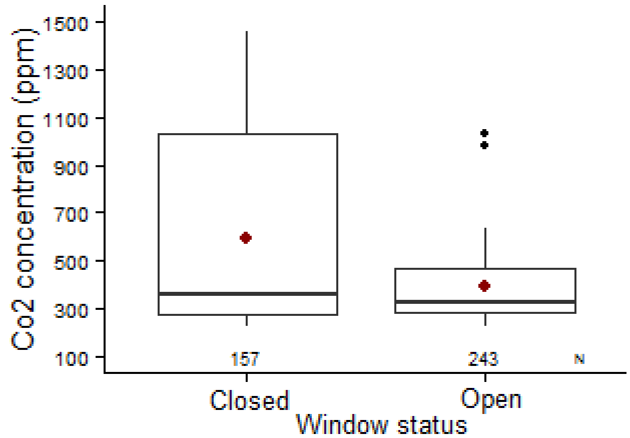

Figure 45. Indoor CO_2 concentration variation with window status during summer in the NV buildings in Jaipur.

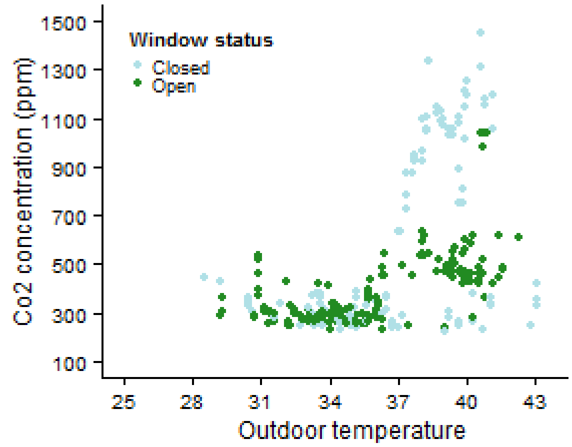

Figure 46. CO_2 concentration during summer in Jaipur.

3.4. Discussion

The indoor temperature range in Alameda during summer is between 20 – 28 ˚C and in winter is between 14 – 28 ˚C. The summer range clearly shows that there is no need for air conditioning while the winter range shows that indoor temperature does not drop proportionally with outdoor temperature. The indoor temperature range during summer in Jaipur is 20 -39 ˚C and during winter is 14 – 33 ˚C. The summer temperature in Jaipur raises the issue of thermal comfort at warm conditions and the role of air conditioners. This topic is elaborated in the thermal comfort chapter (5) and mixed-mode buildings chapter (6). During winter, the indoor temperature does not go below 14 ˚C in Jaipur. This might be because the outdoor temperature during winter in Jaipur has a mean value of 20 ˚C.

Indoor temperature is 5 ˚C warmer than outdoors during summer in the Alameda building while it is 5 ˚C cooler than outdoor during summer in the Jaipur buildings. The warm indoor conditions of Alameda is mainly because of high internal heat gains and low thermal mass. It should be noted that the mean outdoor temperature in Alameda during summer is 18 ˚C and so a 5 ˚C increase in indoor temperature might not cause an overheating risk. In Jaipur, buildings are designed for warm climates and have high thermal mass. Thus the indoor conditions are cooler than outdoor during summer.

Indoor humidity level in Alameda is below 50% in the majority of the observations, while it goes above 60% in 40% of the observations in Jaipur. However, occupants did not perceive these conditions to be very humid even in conditions with high indoor temperature and humidity (Figure 32). This could be mainly because of the high air speed that was in the range of 0.2 – 1.2 m/s. The implications of these findings are huge. Dehumidification is arguably one of the key roles of air conditioning in a warm climate. But decoupling the latent and sensible heat load is challenging and buildings often end up getting over cooled. Ensuring adequate air movement through building design or by ceiling fans is definitely a sustainable way of providing comfort in the buildings that are yet to be built.

The annual mean CO_2 level in the NV building in Alameda (515 ppm) and Jaipur (538 ppm) shows that CO_2 level in NV buildings are well within acceptable limits of 1000 ppm, unlike the AC buildings in Jaipur where the CO_2 levels go to a maximum of 8000 ppm. High occupant density could be one of the main factor contributing to the high CO_2 levels in AC buildings. For comparison, the average office floor area per occupant in government offices the US is 20 m^2, while it is only 5-10 m^2 in Indian offices (Singh et.al. 2013).

In NV buildings in Alameda and Jaipur, indoor CO_2 levels are significantly higher when the windows are closed as compared to when they are open (Figure 43, Figure 44 and Figure 45). Although operable windows improve ventilation, they are accompanied with the problem of bringing in outdoor noise and pollutants, especially in densely populated cities like Jaipur. Such challenges of natural ventilation need to be approached not at a building level but in a more holistic perspective by extending the evaluation framework outside the building. For instance, dust is one of the main concerns for opening a window in Jaipur. One possible way to approach this problem is to install window screens. This is an example of a building level solution which is a quick fix but has limited long term implications because the dust problem still persists outdoors. Moreover, the screens themselves might interfere with window operation. Another alternative is to create awareness about the benefits of natural ventilation among the people and motivate them to develop the landscape so as to reduce the dust particles in the outdoor air. This is an example of a holistic perspective where the same issue of dust is approached by moving the solution space outside the building and engaging the community.

Chapter 4: Behavioral adaptation and modeling

4.1. Introduction

Adjusting clothing, windows and fans are the three most commonly studied adaptive actions. They are important from the energy saving point of view because they allow occupants to adapt over a wider range of indoor temperature and mainly in conditions which are away from the PMV defined neutrality.

Field studies have found that if allowed to dress freely, occupants dress lighter in summer and heavier in winter. Analyzing the ASHRAE 884 and 921 database, Schiavon and Lee found that the median clo values were similar in AC and NV buildings in California. During summer, it was 0.58 in AC buildings and 0.55 in NV buildings. During winter, the median clo value was 0.66 in AC and 0.69 in NV buildings. Clothing was related highest with outdoor temperature (Schiavon and Lee 2012). Carli and Olesen evaluated data from AC and NV buildings from 30 cities world-wide and found a good correlation ($R^2 = 0.72$) between clo value and outdoor temperature in NV buildings and a poor correlation for AC buildings ($R^2 = 0.07$) (De Carli 2007). Clothing adaptation is often restricted by rigid dress codes. Morgan and de Dear did an interesting study in Sydney, Australia to evaluate dress code implication on clothing choice in two locations; a suburban shopping mall (with free dress style) and a call center with a rigid dress code from Monday – Thursday and a free dress style on Fridays. The clo values in the shopping mall varied by season while it was constant in the call center during business days. During the free dress day at the call center, clo levels correlated significantly with outdoor temperature (Morgan and de Dear 2003).

Some studies have found that operable windows are preferred more than other adaptive actions such as adjusting clothing, taking a cool drink and controlling solar glare (Barlow and Fiala 2007, Feriadi and Wong 2004). Some of the benefits of operable windows are that they bring in fresh air, increase air movement and occupants feel connected with the outdoors. When natural wind is not sufficient to provide air movement, fans are one way to provide the additional air movement. In a hot climate like North India or Iraq, having air movement can be equivalent to a 4 ˚C drop in temperature (Nicol 1974). Compared to fans, window interaction has been widely studied and an overview of the different window interaction models is presented below.

4.1.1. Window opening models

Scheduling window status is crucial while modeling a naturally ventilated building using energy simulation programs. From a qualitative point of view, understanding occupants' window interaction is helpful for building designers to know under what conditions people interact with windows. Both these needs have led to numerous studies where researchers monitored window status and developed empirical models to explain the window status and action (opening and closing) using predictor variables such as indoor/outdoor temperature, CO_2 and occupant's arrival (Andersen et.al. 2013, Dutton and Shao 2010, Haldi and Robinson 2008, Haldi and Robinson 2009, Nicol 2001, Rijal 2007, Rijal 2008, Yun and Steemers 2008). This section presents a literature review of window modeling studies, to evaluate the variables that have been considered and those that need to be considered in a window interaction model.

Over the past years, researchers have used different methods to model window interaction. Fritsch performed a pioneering study of mathematically modeling window interaction by developing a stochastic markov chain model that predicted window opening angle (Fritsch 1990). However, the most widely used method to model window interaction is the discrete choice approach of logit/probit model (Haldi and Robinson 2008; Nicol 2001; Rijal 2007; Rijal 2008).

Studies have found that the occupant's routine habit is an important variable influencing occupant's interaction with windows. Herkel et.al. did a field study in 21 individual office buildings in Freiburg, Germany and concluded that when an occupant arrives at the desk, opening a window is habitual just as closing it while leaving the desk at the end of the day (Herkel 2005). Yun and Steemers found the same result in a field study in a private two person office; window state remained unchanged from that set on arrival until the occupants' departure. An interesting approach in their method was the development of separate sub-models for window opening on arrival and closing on departure (Yun and Steemers 2008). This finding shows a subtle aspect of occupant adaptation where they consciously/subconsciously interact with windows. It also suggests that interaction with windows need not necessarily be driven by physical environmental parameters.

Considering the physical environmental parameters, window opening or closing could be triggered by temperature. However, there is not yet consensus in the research literature regarding whether indoor temperature is a stimuli for opening windows and outdoor temperature for closing or vice versa. Fritsch in his early study proposed outdoor temperature to be a better predictor of window opening angle than indoor temperature because room temperature remained relatively constant throughout the year and it could not be easily calculated for a non-existent building (Fritsch 1990). The limitation of predicting indoor temperature is a valid argument because the main building energy simulation softwares existing then were only DOE2, BLAST and an initial version of Transys (IBPSA-USA). However, this limitation has been overcome with the advent of new user friendly building energy simulation softwares.

Following Fritsch's study in 1990, there have been other field studies that evaluated the role of temperature on window opening. Nicol modeled a window state logit model from a database that came from UK, Pakistan and different parts of Europe (Nicol 2001). As the model was intended to feed into a simulation program, Nicol proposed the use of only outdoor temperature as an explanatory variable since outdoor temperature is an input in most simulation programs (Nicol 2001). However, Nicol and Humphrey later proposed indoor temperature to be a better predictor than outdoor temperature (Nicol and Humphreys 2004). Haldi and Robinson modeled two separate logits of proportion of window opened with indoor and outdoor temperature and found that indoor temperature was a better driving stimulus to predict window opening than outdoor temperature. A multivariable logistic regression of window opening with both; indoor and outdoor temperature did not increase the prediction accuracy (Haldi and Robinson 2008). Two other window monitoring studies in the UK, one conducted during summer and the other yearlong, also found indoor temperature to be a better predictor of window interaction than outdoor temperature (Dutton and Shao 2010, Yun and Steemers 2008). On the contrary, a yearlong study in 14 Danish dwellings by Anderson et.al and a yearlong study in Germany in 21 individual German offices by Herkel found strong correlation between window opening and outdoor temperature (Andersen 2013; Herkel 2008).

Another hypothesis that is proposed for window interaction is that occupants open windows as the indoor temperature increases while the outdoor is comparatively cool and they begin to close them when the indoor gets overly warm due to influx of hot outdoor air. Based on this hypothesis and some descriptive statistics, Rijal developed a window opening model which took into consideration the adaptive hypothesis. A threshold of 2 ˚C was determined for the difference between operative and comfort temperature to predict window status. An interesting step taken in this study was to calculate the cooling potential of window opening. Comparing the globe temperature on weekends when the windows were closed, and weekdays when they were open, gave a cooling potential of 2.2 K. This cooling effect was found to be higher in light weight buildings than heavy weight (Rijal 2008).

There is a consistent opinion about the influence of season on window opening. More windows were found open in summer than in winter/swing season (Herkel 2008, Rijal 2007). The influence of season on window opening is an important variable to consider mainly because it illustrates occupant behavior in response to the outdoor climate. Following an extensive literature review, Fabi et.al. identified the following variables as non-drivers of window interaction- wind direction, rainfall, income, thermal sensation, day of week, wood burning stove, wind speed, age and solar radiation (Fabi 2012). One of the non-intuitive parameters in this list is thermal sensation. One would expect occupants to open windows when they feel warm but it has been found that other factors viz. time of day and the need to bring in fresh air override the discomfort driven interactions (Dutton and Shao 2010). Dutton and Shao studied a school building for one year and developed a multinomial logit model for window opening (Dutton and Shao 2010). They found that occupants opened the windows during morning hours especially during the unheated period to bring in fresh air and also to precool the space in anticipation of warm afternoons. Moreover, they found that the probability of a window being open is related to the number of windows already open. This finding is important in the context of window modeling presented in this thesis because the Alameda building has multiple windows in a room and it could be very likely that the window interaction is influenced by the number of windows already open.

The following insights can be drawn about window modeling from the above studies:

- Window state is strongly influenced by occupant’s routine habits; they tend to open windows on arrival and close it on departure.
- Logistic regression is the most widely used statistical method to model window interaction.
- Influence of indoor and outdoor temperature on window interaction is debated although most of the studies have found at least one of the two variables to be significant.
- Window state is predicted mainly by using indoor/outdoor temperature as the explanatory variable. This is based on the assumption that window opening is primarily affected by temperature. There is a need to develop a robust model that takes into account variables beyond temperature such as time of day, season and inertia.

Since the methods of data collection are different in Alameda and Jaipur, window opening in both the climates are evaluated separately. The Alameda study being longitudinal, allows for a detailed window level model. The Jaipur study being transverse, allows to capture more variation in window choices.

4.2. Analysis method

4.2.1. Logistic regressions

Discrete choice model

Discrete choice theory is a method of modeling an individual's choice preference when presented with two or more alternatives. The binary choice model is formulated by defining a utility function (U) for each alternative available to the individual. The utility function consists of a systematic/deterministic part (V) and the random part (ε). This utility function holds some meaning only in comparative sense and not absolute which is to say, only difference in the utilities matter (Ben Akiva and Lerman 1985).

$$U_{in} = V_{in} + \varepsilon_{in}$$
$$U_{jn} = V_{jn} + \varepsilon_{jn}$$

Where *i* is the alternative for decision maker 'n'.

An underlying assumption in discrete choice theory is that decision makers are utility maximizers. Thus if presented with two alternatives *i* and *j*, the probability that a decision maker 'n' chooses alternative *i* is given by

$$\begin{aligned} P_n(i) &= Pr(U_{in} \geq U_{jn}) \\ &= Pr(V_{in} + \varepsilon_{in} \geq V_{jn} + \varepsilon_{jn}) \\ &= Pr(\varepsilon_{jn} - \varepsilon_{in} \leq V_{in} - V_{jn}) \end{aligned}$$

The systematic component consists of the explanatory variables **x** that are linear in the parameters with coefficients **β** which need to be estimated. It should be noted that x can be polynomial, piecewise linear, logarithmic or exponential, that is to say, linearity in parameters is not the same as linearity in attributes (Ben Akiva and Lerman 1985).

$$V_{in} = \boldsymbol{\beta}'\mathbf{x_{in}}$$
$$\boldsymbol{\beta} = [\beta_1, \beta_2, \beta_3, \dots \dots, \beta_k]$$
$$\mathbf{x} = [x_{in1}, x_{in2}, x_{in3}, \dots \dots, x_{ink}]$$
$$V_{in} = \beta_1 x_{in1} + \beta_2 x_{in2} + \beta_3 x_{in3} + \dots \dots + \beta_k x_{ink}$$
$$V_{jn} = \beta_1 x_{jn1} + \beta_2 x_{jn2} + \beta_3 x_{jn3} + \dots \dots + \beta_k x_{jnk}$$

Binary logit model

In a binary logit model, the assumption is that $\varepsilon_n = \varepsilon_{jn} - \varepsilon_{in}$ is logistically distributed which is same as assuming ε_{jn} and ε_{in} are independent and identically (IID) Gumbel distributed. The variance of ε_{jn} and ε_{in} is $\frac{\pi^2}{6\mu^2}$, where μ is the scale parameter. For computational convenience the value of μ is set to 1 (Ben Akiva and Lerman 1985). The choice probability for alternative *i* is given by

$$P_n(i) = \frac{1}{1 + e^{-\mu(V_{in}-V_{jn})}}$$
$$= \frac{e^{\mu V_{in}}}{e^{\mu V_{in}} + e^{\mu V_{jn}}}$$

While working with more than one panel dataset (multiple observations over a period of time), a correlation might exist between the observations of a particular dataset. For instance in the Alameda study, hourly window observations are recorded for each window. A correlation might exist between the observations for each window. To take into account this correlation, the assumption that μ is equal to 1 is relaxed. Coefficients $\mu_1,\ \mu_2, \mu_3, \mu_4, \dots \dots, \mu_n$ are introduced for each window and one of the μ is constrained to 1.

Maximum likelihood estimation

In a binomial choice model, the parameters estimates $\boldsymbol{\beta} = [\beta_1, \beta_2, \beta_3, \dots \dots., \beta_k]$ are calculated by maximizing the likelihood function. If the choice variable is defined as

$$y_{in} = \begin{cases} 1 & if\ decision\ maker\ n\ chose\ alternative\ i \\ 0 & if\ decision\ maker\ n\ chose\ \ alternative\ j \end{cases}$$

The likelihood function is

$$L^*(\beta_1, \beta_2, \beta_3, \dots \dots., \beta_k) = \prod_{n=1}^{N} P_n(i)^{y_{in}}\, P_n(j)^{y_{jn}}$$

The log likelihood is then written as

$$L(\beta_1, \beta_2, \beta_3, \dots \dots., \beta_k) = \sum_{n=1}^{N} [y_{in} log P_n(i) + y_{jn} log P_n(j)]$$

The parameter estimates $(\beta_1, \beta_2, \beta_3, \dots \dots., \beta_k)$ are obtained by differentiating the log likelihood function and setting the partial derivative to zero (Ben Akiva and Lerman 1985).

Goodness of fit

Rho bar squared and Nagelkerke's R-squared are the two metrics of goodness of fit used in this section to determine how well the logit model fits the data. Both the metrics measure the performance of a model with the estimated parameters to a model where the estimated parameters are zero (null model). Therefore the interpretation of rho bar squared and Nagelkerke's R-squared is not the same as r-square of a linear regression. R-square in a linear regression shows how much variance in the dependent variable is explained by the independent variable. However, when comparing two models estimated on the same dataset and alternatives, it is can be concluded that model with higher ρ fits the data better (Train 2009).

Rho bar squared is defined as

$$\rho^2 = 1 - \frac{LL(\beta)}{LL(0)}$$

Nagelkerke’s R squared is similar to rho bar squared which gives a comparison of the fitted model to a null model. The only difference is that it takes into consideration the number of observations in the dataset (Haldi 2010; Nagelkerke 1991).

Nagelkerke’s R- squared is defined as

$$R_n{}^2 = \frac{1 - \left\{\frac{LL(\beta)}{LL(0)}\right\}^{\frac{2}{N}}}{1 - LL(0)^{\frac{2}{N}}}$$

Where N is the number of observations in the dataset

Ordinal logit

An ordinal logit model is fitted when the responses are ordered. In this study, the ‘number of windows open’ is the ordered response which varies from 0 to 5 in the front room and from 0 to 3 in the back room. A utility (U) function is defined for each response with thresholds at $\tau = [\tau_0, \tau_1, \tau_2, \tau_3, \dots \dots, \tau_k]$. The utility consists of the systematic and the random component. As in a binary logit model, the systematic part is defined as $\boldsymbol{\beta}'\mathbf{x}$ (Train 2009).

The decision maker choses an alternative based on the value of the utility. Figure 47 shows the utility thresholds for different number of windows open. If the utility (U) is less than τ_0, then no window is open. If U is greater than τ_0 and less than τ_1, then one window is open.

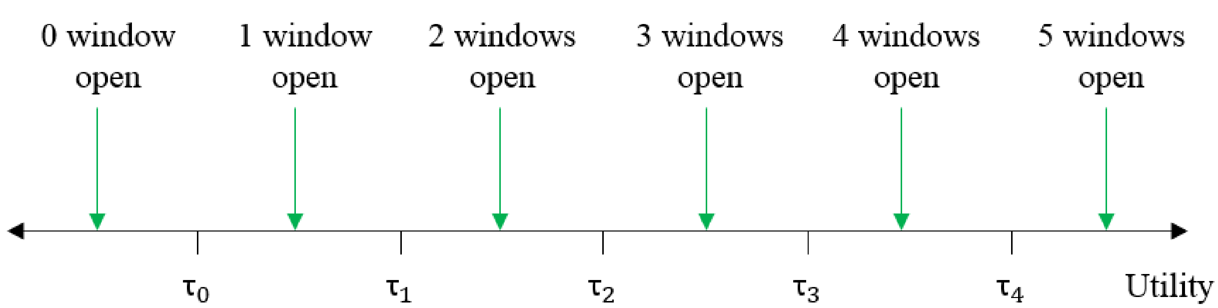

Figure 47. Utility thresholds for the ordinal logit model.

The probabilities can be written as

$$\begin{aligned} P(0\ win\ open) &= Pr(U < \tau_0) \\ &= Pr(\beta'\mathrm{x} + \varepsilon < \tau_0) \\ &= Pr(\varepsilon < \tau_0 - \beta'\mathrm{x}) \\ &= \frac{e^{\tau_0 - \beta' x}}{1 + e^{\tau_0 - \beta' x}} \end{aligned} \quad (1)$$

$$\begin{aligned} P(1\ win\ open) &= Pr(\tau_0 < U < \tau_1) \\ &= Pr(\tau_0 < \beta'\mathrm{x} + \varepsilon < \tau_1) \\ &= Pr(\tau_0 - \beta'\mathrm{x} < \varepsilon < \tau_1 - \beta'\mathrm{x}) \end{aligned} \quad (2)$$

$$\begin{aligned} &= Pr(\varepsilon < \tau_1 - \beta'\mathrm{x}) - Pr(\varepsilon < \tau_0 - \beta'\mathrm{x}) \\ &= \frac{e^{\tau_1 - \beta'\mathrm{x}}}{1 + e^{\tau_1 - \beta'\mathrm{x}}} - \frac{e^{\tau_0 - \beta'\mathrm{x}}}{1 + e^{\tau_0 - \beta'\mathrm{x}}} \end{aligned}$$

4.3. Results

4.3.1. Clothing

The mean clo value during summer in Alameda is 0.55 (SD = 0.09) while in Jaipur it is 0.45 (SD = 0.14). During winter, the mean clo value in Alameda is 0.72 (SD = 0.13) and in Jaipur is 0.56 (SD = 0.2). Analyzing selected studies from the ASHRAE 884 and 921 database in NV buildings in California, Schiavon and Lee found median summer clo value to be 0.55 and the median clo value in winter to be 0.69 (Schiavon and Lee 2012).

Clothing variation is influenced by different quantitative parameters such as indoor, outdoor, running mean temperature or outdoor temperature at 6am. Analysing a database of field studies worldwide, De Carli et al. concluded that outdoor temperature at 6am best explains the variability in clothing in naturally ventilated buildings (R^2=0.3) (De Carli 2007). For the Alameda and Jaipur dataset, indoor temperature, outdoor temperature and running mean temperature are selected as the predictor variables. Correlation between them is shown in Figure 48 and Figure 49. An interesting result from this correlation matrix is that in the mild climate of Alameda, clothing is correlated highest with outdoor running mean temperature while in Jaipur it is correlated highest with indoor temperature (Figure 48 and Figure 49).

Indoor temperature drops out as an insignificant variable in Alameda and outdoor running mean temperature drops out in Jaipur when a multivariable linear regression is fitted between clo and explanatory variables, indoor and outdoor running mean temperature. The Alameda model explains the variance better than the Jaipur model; R^2 in Alameda is 0.35 while it is 0.2 in Jaipur (Table 6). This shows that occupant's wardrobe decision in Alameda is influenced mainly by outdoor temperature while people in Jaipur decide their clothing based on indoor temperature.

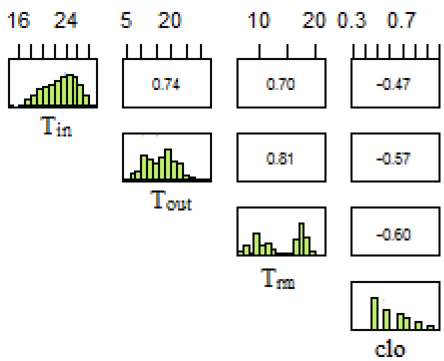

Figure 48. Correlation matrix between clo and temperature variables in Alameda.

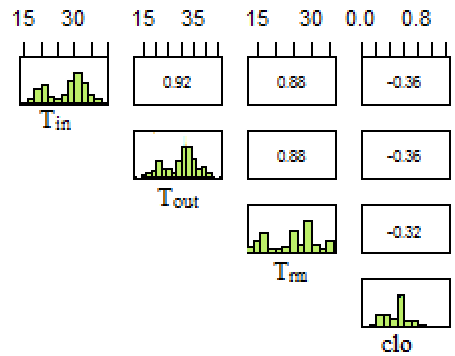

Figure 49. Correlation matrix between clo and temperature variables in Jaipur.

Location	Coefficient	Value	Std Error	p value	R^2
Alameda	Intercept	0.914	0.027	< 0.001	0.35
	T_{indoor}	~0	0.002	0.468	
	$T_{running\ mean}$	-0.019	0.001	< 0.001	
Jaipur	Intercept	0.947	0.021	< 0.001	0.22
	T_{indoor}	-0.016	0.002	< 0.001	
	$T_{running\ mean}$	~0	0.002	0.661	

Table 6. Coefficients of linear regression between clothing and explanatory variables - indoor temperature and running mean temperature.

A possible argument could be that since indoor and outdoor temperatures are correlated, it is inappropriate to conclude that occupants' clothing decisions in Alameda are oblivious of indoor temperature. To evaluate this argument further, Figure 50 shows the boxplot of clo values binned per two degree running mean outdoor temperature. Statistically significant difference between the mean of the clo values in each temperature bin is shown by a dark red star above the x axis. In three of the five overlapping bins, occupants in Jaipur dressed significantly heavier than those from Alameda ($p < 0.05$). Figure 51 shows the indoor temperature binned per 2 ˚C outdoor temperature. Indoor temperature in Jaipur is significantly cooler than Jaipur in the overlapping bins (Figure 51). This shows that occupants in Jaipur dress heavier to compensate for the cool indoor temperatures.

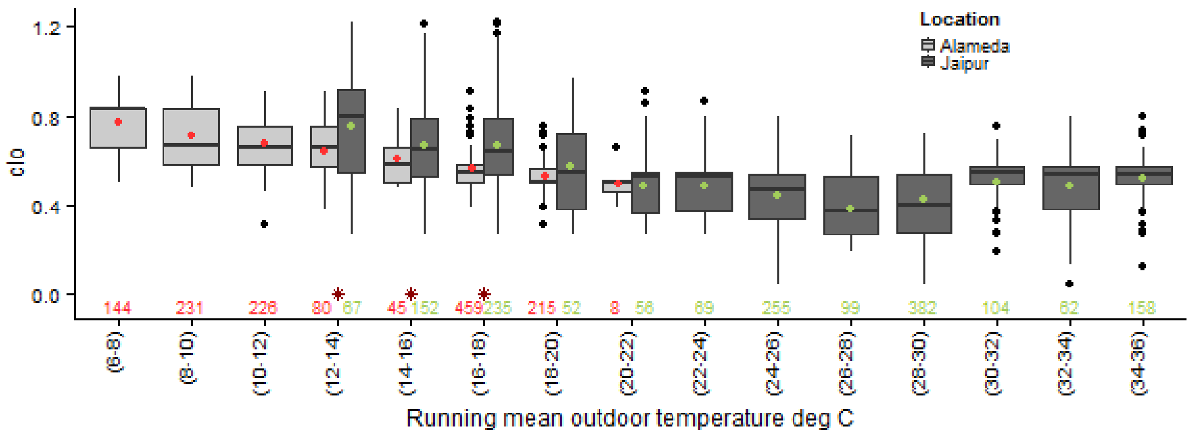

Figure 50. Clo levels binned by running mean outdoor temperature.

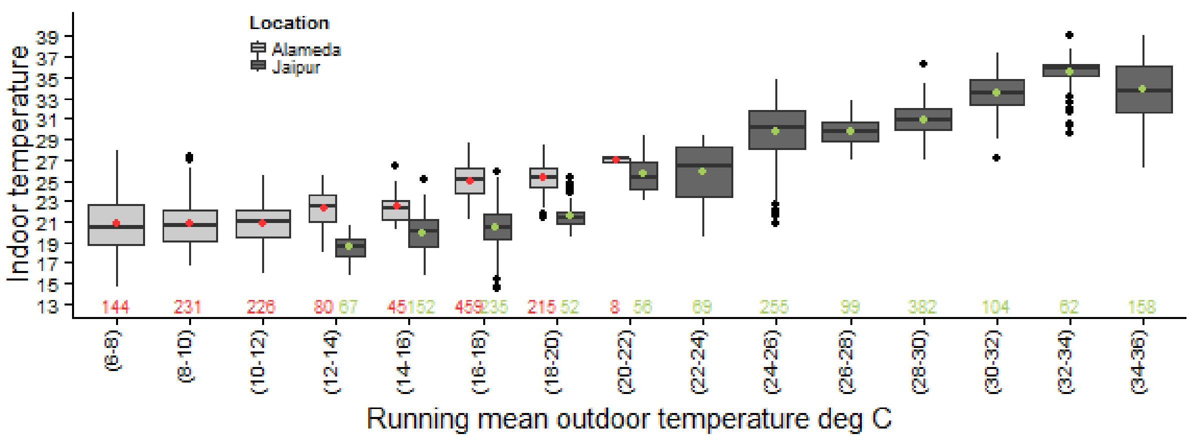

Figure 51. Indoor temperature versus running mean temperature boxplot.

4.3.2. Window adjustment in Alameda

Window status vs window action

Occupant window interaction can be modeled either as window status or window action. Anderson et.al in their paper on window modeling in Danish buildings argue that window action is a better metric than window status to evaluate window interaction because modeling window status could give misleading results. For instance, in cold climates indoor temperatures would be cold when windows are open and not when they are closed. This way, the status model would estimate that the probability increases with decrease in indoor temperature (Andersen 2013). Although, this seems to be a reasonable argument, it has some shortcomings. If a window is found open at cold indoor conditions, it means occupants prefer to have it open and don't mind the low indoor temperatures. The question then becomes what is the temperature threshold until which the window remains open?

However, one drawback of modeling window status is that the current state of a window depends heavily upon the previous state. This can be taken into account by introducing an inertia term into the utility function. Therefore in this thesis, window interaction is modeled as window status.

Selection of explanatory variables

The main explanatory variables monitored in this study are Indoor temperature, difference between indoor and outdoor temperature, time of day, season, CO_2 concentration, wind velocity and wind direction. Significant data of CO_2 concentration, wind velocity and wind direction were missing during the winter. Thus, these three variables are not included in the model. Although wind velocity and direction have been found to not influence window interaction, CO_2 concentration significantly affected it (Dutton and Shao 2010, Fabi 2012).

Variables in the model are of two types- continuous and discrete. Table 7 shows the description of each of the variable type. Indoor temperature was included in the model through the variable T_{diff} which captures the effect of the difference between indoor and outdoor temperature. For instance, a positive coefficient of T_{out} and a positive coefficient of T_{diff}, would mean that the window is likely to be open as the outdoor temperature gets warmer but only until the outdoor is cooler than the indoors.

Time of day is divided into three categories based on the occupancy graph (Figure 52) which shows the total percent of time the office was occupied during every hour of the day by at least one person. Occupants in this office generally arrive in the morning between 7-11 am and leave between 5-8 pm. These two times of the day are captured in the morning hour (7am – 11am) and the evening hour (4 – 8 pm) of the 'time of day' variable. Afternoon hour (12pm – 3pm) is when people are mostly at their desk. Each time stamp is rounded to the nearest hour. For example, 10:20 am is rounded to 10am and 10:40 am is rounded to 11am.

Season is split into summer (June-October) and winter/spring (November to May). Winter and swing needed to be combined because windows are not opened in winter. The logit model can be estimated only if the choice (window being open) is exercised in all the levels of the explanatory variable. The inertia variable takes into account the phenomenon that the current window status is heavily influenced by the previous state. If the window is open in the previous hour, occupants might have some resistance to interact with it unless overpowered by some stronger factor such as thermal discomfort or noise from outdoors. Inertia is a binary variable that takes the value of 1 or 0 depending on the window state in the previous hour. If the window was open in the previous hour, the inertia variable is equal to 1 and 0 other wise. This is defined as the 'open inertia' in the window-open utility function. If the window was closed in the previous hour, the inertia variable is equal to 1 and is defined as the 'close inertia'. However, 'close inertia' enters the utility function of a window being closed.

Another important thing to consider during the selection of explanatory variables is their mutual correlation. A possible critique might be that including two correlated variables in the logit model would compromise its predicting power. For example, if outdoor temperature and season are perfectly correlated and are significant, then including both the correlating variables would dampen the coefficients of the model. Figure 53 shows the correlation between variables for the complete dataset (all windows included). There are no variables that are correlated strongly except outdoor temperature and temperature difference (R= -0.85). This just means their coefficients and significance in the model should be carefully interpreted.

Variable	Type	Levels
Outdoor temperature (T_{out})	Continuous	-
Indoor- Outdoor temperature (T_{diff})	Continuous	-
Time of day	Discrete	Morning hour- MH (7am-11am) Afternoon hour- AH (12pm-3pm) Evening hour- EH (4pm-8pm)
Season	Discrete	Summer- (Jun-Oct) Winter/Swing-(Jan-May, Nov-Dec)
Inertia	Discrete	1- If Window state was same in the previous hour 0 – Otherwise
Alternative specific constant	Constant	-

Table 7. Variables included in window status model.

Figure 52. Hourly occupancy during working days.

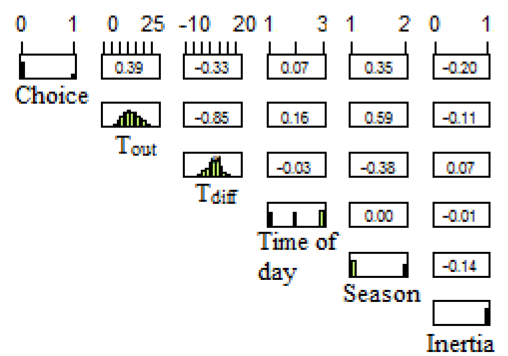

Figure 53. Correlation between explanatory variables that will be included in the window status model.

Binomial logit model for window status- (Constrained and unconstrained models)

The influence of each predictor variable like outdoor temperature, temperature difference and time of day might be different for each individual. The yearlong monitoring of each window in the Alameda building allows for the evaluation of idiosyncratic parameters that influence certain windows. Two extreme scenarios are tested with two different models. The first model is a constrained model where the β's are assigned to be same for each parameter across all windows. Serial correlation between windows is taken into account by setting only one μ to be equal to 1 for a single window and estimating it for other windows (Table 8). The utility function is given in equation 3. The second model is an unconstrained model where the scale parameter μ is set to 1 and different β's are estimated for each predictor variable per window. In other words, the assumption is that every predictor variable affects each window differently. The utility function is given in equation 4.

Coefficient interpretation of constrained model (Table 8)

- β_{Tout} is the coefficient of outdoor temperature and is positive. This means a window is more likely to be open as the outdoor temperature increases
- β_{Tdiff} is the coefficient of temperature difference and is not significant. However, as indoor and outdoor temperatures are correlated, the insignificant parameter needs to be evaluated carefully. The insignificance might be because during winter, occupants turn on heaters and the indoor temperature stays warmer compared to the outdoor. Windows are mostly closed during winter and thus the status is explained better by the outdoor temperature.
- β_{AH} and β_{EH} are the coefficients of time of day variable for afternoon and evening hour. Both of them are significant and have a negative sign which means a window is more likely to be found open during morning hour compared to afternoon or evening.
- β_{summer} is the coefficient of summer season and is significant. As expected, it has a positive sign which means there is a higher chance of a window being open during summer compared to winter/swing.
- ASC_{open} is the alternative specific constant for open position. It captures the mean difference in utilities when all coefficients are zero. ASC is defined only for window open utility function as only the difference between the utilities matter. ASC_{open} is negative which means the window is most likely to be found closed when all coefficients are zero.

$$V_{open} = \{(\beta_{Tout} * Tout + \beta_{Tdiff} * Tdiff + \beta_{AH} * AH + \beta_{EH} * EH + \beta_{summer} * Summer + \beta_{Inertia} * (Open\ Inertia - Close\ Inertia) + ASC_{open})\} \{\mu_1 * winf3 + \mu_2 * winf4 + \ldots\ldots + \mu_6 * winb6\} \quad (3)$$

$$V_{close} = 0$$

Variable	Coefficient	Value	Std Error	t-test	p-value	
Outdoor temperature	β_{Tout}	0.143	0.022	6.52	0	*
Tdiff	β_{Tdiff}	0.0294	0.025	1.20	0.23	
Afternoon hour	β_{AH}	-0.65	0.113	-5.75	0	*
Evening hour	β_{EH}	-2.31	0.162	-14.26	0	*
Summer season	β_{summer}	1.23	0.116	10.60	0	*
Inertia	$\beta_{inertia}$	3.15	0.118	26.66	0	*
Alternative specific constant	ASC_{open}	-3.51	0.506	-6.93	0	*
Scale parameter 1	μ_1	1	-	-	-	-
Scale parameter 2	μ_2	0.942	0.044	21.29	0	
Scale parameter 3	μ_3	0.939	0.044	21.24	0	
Scale parameter 4	μ_4	1.04	0.050	20.65	0	
Scale parameter 5	μ_5	0.961	0.049	19.57	0	
Scale parameter 6	μ_6	0.905	0.045	19.96	0	*
Log-likelihood	-2628.86					
Rho bar	0.798					
Number of parameters	12					

Table 8. Coefficients of the constrained logit model.
(Same β for each parameter across all windows, μ's are estimated)

Coefficient interpretation of unconstrained model (Table 9)

- β_{Tout}, the coefficient of outdoor temperature is significant for window f6 from the front room and windows b1 and b6 from the back room. The positive coefficient indicates that all these windows are likely to be found open as the outdoor temperature increases.
- β_{Tdiff}, the coefficient of temperature difference is significant for window f3 from the front room and windows b1 and b6 from the back room. β_{Tdiff} of window f3 is negative which means it is most likely to be found open when the outdoor temperature is warmer than indoor. Although this is counter-intuitive, it is partly explained by the fact that outdoor temperature does not go very high. So this window probably stays open to provide air movement when outdoors is warmer than indoors. β_{Tdiff}'s of windows b1 and b6 are positive which mean they are more likely to be found open when indoors is warmer than outdoors compared to the vice-versa situation.
- β_{AH}, the coefficient for afternoon hour is significant for windows f3, f4, b1 and b6 while β_{EH}, the coefficient for evening hour is significant for all windows in both the rooms. All the significant coefficients of β_{AH} and β_{EH} are negative which means these windows are more likely to be found open during morning hours compared to afternoon and evening hours.
- β_{summer}, the coefficient for summer season is significant for all windows except window b1. As expected, the coefficients have a positive sign which means the windows are more likely to be found open in summer than winter /swing.
- $\beta_{inertia}$, the coefficient for inertia is significant for all windows and has a positive sign as expected which means if a window was open in the previous it is likely to be open now.
- ASC_{open}, the alternative specific constant is negative which means the windows are likely to be found closed when the coefficients are all zero

A summary of the significant variables influencing each window along with the sign of the coefficient is shown in Figure 54.

$$
\begin{aligned}
V_{open} = \{ & \big(\beta_{Tout,f3} * Tout + \beta_{Tdiff,f3} * Tdiff + \beta_{AH,f3} * AH + \beta_{EH,f3} * EH + \beta_{summer,f3} * Summer \\
& + \beta_{Inertia,f3} * (Open\ Inertia - Close\ Inertia) + ASC_{f3}\big) * winf3 + \\
& \big(\beta_{Tout,f4} * Tout + \beta_{Tdiff,f4} * Tdiff + \beta_{AH,f4} * AH + \beta_{EH,f4} * EH + \beta_{summer,f4} * summer + \\
& \beta_{Inertia,f4} * (Open\ Inertia - Close\ Inertia) + ASC_{f4}\big) * winf4 + \\
& \ldots\ldots\ldots\ldots \\
& \ldots\ldots\ldots\ldots \\
& \big(\beta_{Tout,b6} * Tout + \beta_{Tdiff,b6} * Tdiff + \beta_{AH,b6} * AH + \beta_{EH,b6} * EH + \beta_{summer,b6} * Summer + \\
& \beta_{Inertia,b6} * (Open\ Inertia - Close\ Inertia) + ASC_{b6}\big) * winb6 \} * \\
& \{\mu_1 * winf3 + \mu_2 * winf4 + \ldots\ldots + \mu_6 * winb6\}
\end{aligned} \tag{4}
$$

$$V_{close} = 0$$

Variable	**Coeff.**	**f3**		**f4**		**f6**		**f8**		**b1**		**b6**	
Tout	β_{Tout}	-0.019		0.085		0.174	*	0.076		0.354		0.382	*
Tdiff	β_{Tdiff}	-0.135	*	-0.056		0.056		-0.025		0.334	*	0.22	*
AH	β_{AH}	-0.928	*	-1.25	*	0.396		-0.406		-0.742	*	-1.09	*
EH	β_{EH}	-1.49	*	-2.48	*	-1.8	*	-2.73	*	-2.48	*	-3.11	*
Summer	β_{summer}	1.99	*	1.36	*	1.31	*	1.31	*	0.174		0.548	*
Inertia	$\beta_{inertia}$	2.99	*	3.1	*	2.91	*	3.41	*	2.76	*	3.03	*
ASC	ASC_{open}	-0.353		-1.57		-4.71	*	-1.95		-8.78	*	-7.93	*
Log-likelihood	-2552.3												
Rho bar	0.804												
Number of parameters	42												

Table 9. Coefficients of the unconstrained logit model.
(Different β for each parameter for each window, all μ's constrained to 1)

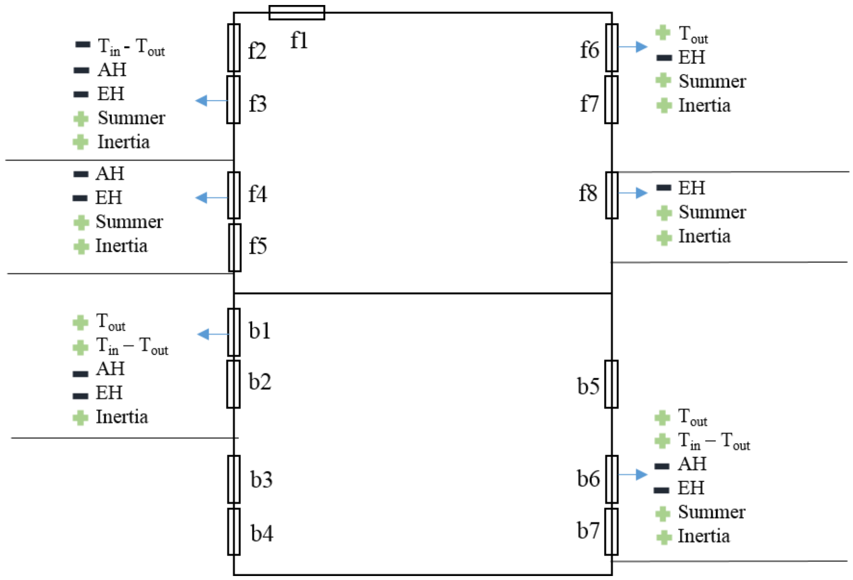

Figure 54. Significant variables affecting window status of individual windows (unconstrained model).

Having estimated the constrained and the unconstrained models, the next step is to identify which of them is better. This is done by using the likelihood ration test. A test static is calculated from the log likelihoods of both the functions and is compared with the critical chi-squared values at 95% confidence from the degree of freedom tail probability distribution chart.

$$t_{static} = -2(Loglik^{constrained} - Loglik^{unconstrained})$$
$$t_{static} = -2(-2628.86 - (-2552.28))$$
$$t_{static} = 153.16$$

Degree of freedom = 42 – 12 = 30
$\chi^2 critical\ (p = 0.05) = 43.77$

Since $\chi^2 critical < t_{static}$, we reject the null hypothesis that the coefficients are similar across all windows. In other words, the unconstrained model is better than the constrained model.

However, the coefficients in Table 9 reveal another interesting pattern. The ASC's of the backroom windows (b1 and b6) are distinctly lower than the front room windows (f3, f4, f6 and f8). This means that the windows in the back room are opened less compared to the front room. Thus to reduce the complexity of having an unconstrained model with 42 parameters, a mid-model is defined where the coefficients for each parameter are constrained to be the same across windows from each room. The utility function is defined in equation 5.

Coefficient interpretation of mid model (Table 10)

- β_{Tout}, the coefficient of outdoor temperature is significant for both the rooms and has a positive sign. As expected, this means there is a higher probability of finding a window open at higher outdoor temperatures.
- β_{Tdiff}, the coefficient of temperature difference (indoor – outdoor) is not significant in the front room but is significant in the back room with a positive sign. β_{Tout} and β_{Tdiff} when interpreted together means that the window is likely to be open as the outdoor temperature increases but when the outdoor gets warmer than indoor, the window is likely to be found closed.
- β_{AH} and β_{EH}, the coefficients of time of day variable are significant for both the rooms. They have a negative sign which means the window is more likely to be found open during morning compared to afternoon or evening.
- Interestingly, β_{summer}, the coefficient of summer season is significant only for the front and not for the back room. As expected, the coefficient has a positive sign which means the windows are more likely to be found open during summer compared to winter/swing.
- $\beta_{inertia}$, the coefficient of inertia variable is significant for both the rooms and has a positive sign, which means inertia contributes positively towards the utility of a window being open.
- ASC_{open} is significant for both the rooms and has a negative sign which means the windows are more likely to be closed when all parameters are zero. An interesting thing to note is that the ASC for the back room is much lower than the ASC for the front room. This difference between coefficients in the front and back room is further evaluated in Table 11 with the covariance matrix where the null hypothesis is that the β's are not significantly different from each other. All variables except afternoon hour and inertia are significantly different for the front and back room. This result shows how predictor variables could be idiosyncratic and how window opening could be different in two adjacent rooms in the same building.

$$V_{open} = \{[(\beta_{Tout,front} * Tout + \beta_{Tdiff,front} * Tdiff + \beta_{AH,front} * AH + \beta_{EH,front} * EH + \beta_{summer,front} * Summer + \beta_{Inertia,front} * (Open\ Inertia - Close\ Inertia) + ASC_{front}) * (winf3 + winf4 + winf6 + winf8)] + [(\beta_{Tout,back} * Tout + \beta_{Tdiff,back} * Tdiff + \beta_{AH,back} * AH + \beta_{EH,back} * EH + \beta_{summer,back} * summer + \beta_{Inertia,back} * (Open\ Inertia - Close\ Inertia) + ASC_{back}) * (winb1 + winb6)]\} * \{\mu_1 * (winf3 + winf4 + winf6 + winf8) + \mu_2 * (winb1 + winb6)\} \quad (5)$$

$$V_{close} = 0$$

Variable	Coeff.	Value	Std error	t-test	p-value	
Tout-Front (C)	$\beta_{Tout,front}$	0.073	0.023	3.15	0	*
Tdiff-Front	$\beta_{Tdiff,front}$	-0.048	0.027	-1.82	0.07	
AH-Front	$\beta_{AH,front}$	-0.49	0.127	-3.86	0	*
EH-Front	$\beta_{EH,front}$	-2.04	0.158	-12.91	0	*
Summer season-Front	$\beta_{summer,front}$	1.47	0.127	11.51	0	*
Inertia-Front	$\beta_{inertia,front}$	3.06	0.071	43.11	0	*
ASC- Front	$ASC_{open,front}$	-1.99	0.539	-3.7	0	*
Tout- Back (C)	$\beta_{Tout,back}$	0.431	0.063	6.82	0	*
Tdiff-Back	$\beta_{Tdiff,back}$	0.352	0.063	5.57	0	*
AH-Back	$\beta_{AH,back}$	-0.947	0.224	-4.23	0	*
EH-Back	$\beta_{EH,back}$	-2.85	0.374	-7.63	0	*
Summer season-Back	$\beta_{summer,back}$	0.271	0.211	1.28	0.2	
Inertia-Back	$\beta_{inertia,back}$	3.06	0.281	10.85	0	*
ASC- Back	$ASC_{open,back}$	-9.88	1.42	-6.94	0	*
μ_2		0.969	0.054	18.09	0	
Log-likelihood	-2606.28					
Rho bar	0.8					
Number of parameters	15					

Table 10. Coefficients of the mid logit model.
(Same β for each parameter across all windows in front and back room, μ's are estimated)

Coefficient1	Coefficient2	Rob. cov.	Rob. t-test	p-value	
Tout-Front (C)	Tout- Back (C)	4.95E-17	-5.32	0	*
Tdiff-Front	Tdiff-Back	1.51E-14	-5.84	0	*
AH-Front	AH-Back	1.14E-13	1.78	0.08	
EH-Front	EH-Back	-3.40E-14	1.99	0.05	*
Summer season-Front	Summer season-Back	-2.41E-14	4.85	0	*
Inertia-Front	Inertia-Back	-4.57E-14	0	1	
ASC- Front	ASC- Back	2.17E-14	5.18	0	*

Table 11. Covariance matrix between front and back room coefficients.

Ordinal logit model for number of windows open

The Alameda building has 8 windows in the front room and 5 windows in the back room. A useful metric to understand overall window interaction is 'number of windows open'. Ordinal logit is used to model the consecutive levels of open windows. The analysis is done separately for the front and back rooms since significant differences were found in window interaction between both the rooms in previous analysis.

In the front room, the vertical dotted lines show the threshold temperatures when the probability of a certain number of windows open is exceeded by a greater number of windows open (Figure 55). In other words, these are the thresholds at which the count of number of windows open increases by one. Probability of '0 window' being open is highest until around 26 ˚C and the probability of more than one window being open gradually increases with temperature. A similar pattern is seen in the back room; probability of 0 window being open is highest until an outdoor temperature of around 26 ˚C. The curve of all three window being open is low.

Coefficients of the ordinal logit model are shown in Table 12 and Table 13.

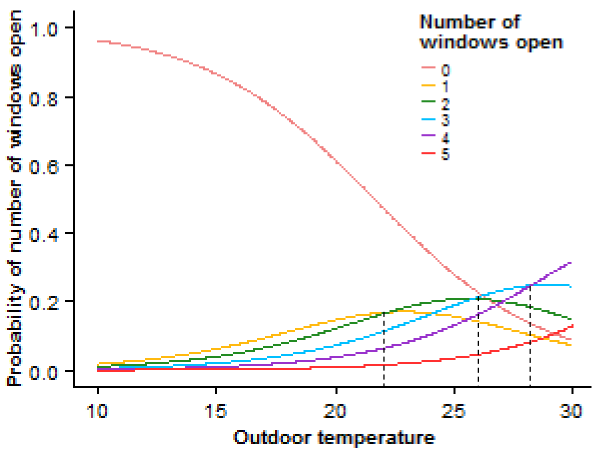

Figure 55. Ordinal logit model for front room.

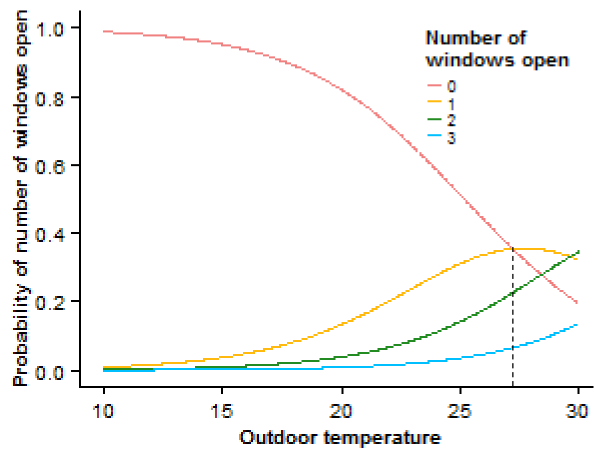

Figure 56. Ordinal logit model for back room.

Coefficient	**Value**	**Std. Error**	**t value**	**p value**	
T_{out}	0.281	0.006	44.513	0	*
τ_1	6.077	0.118	51.442	0	*
τ_2	6.767	0.124	54.611	0	*
τ_3	7.615	0.132	57.867	0	*
τ_4	8.635	0.143	60.380	0	*
τ_5	10.332	0.188	54.859	0	*

Table 12. Coefficients of ordinal logit for front room.

Coefficient	Value	Std. Error	t value	p value	
Tout	0.293	0.010	30.525	<0.001	*
τ_1	7.381	0.2	36.88	<0.001	*
τ_2	8.869	0.217	40.927	0	*
τ_3	10.639	0.26	40.970	0	*

Table 13. Coefficients of ordinal logit for back room.

4.3.3. Window adjustment in Jaipur

During summer, windows are open in 61% of the observations (243 out of 400) while in winter it is 15% (83 out of 553). Figure 57 shows the percentage of windows open in each bin of indoor and outdoor temperature. Only those bins with two or more observations are shown. Windows are mostly closed when the outdoor temperature is below 27 ˚C. However, there is no distinct threshold for indoor temperature. The color gradient in Figure 57 shows that more windows are open as the outdoor temperature increases. However, when the outdoor temperature is above 38 ˚C, windows are open in only 55 % of the observations (63 out of 115). This could be possibly because the warm outdoor air is not preferred inside the building.

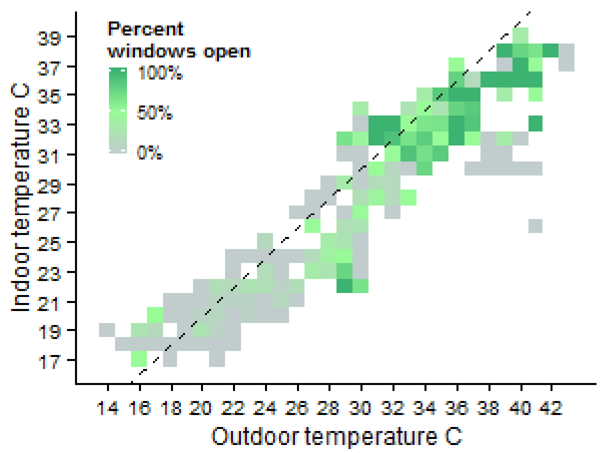

Figure 57. Percentage of window open per degree bin of indoor and outdoor temperature in Jaipur.

Figure 58 and Figure 59 show the hourly percentage of windows open during summer and winter respectively. Window data was available only from 10am – 7pm. Percentage of windows open is almost the same during the morning (10 – 11 am) and afternoon hours (12pm – 3pm). Compared to both these times of the day, more windows are open in the evening hour bin (4 – 5 pm); the bins at 6 and 7pm have very few observations (Figure 58). During winter, there is no clear trend in window status through the day (Figure 59).

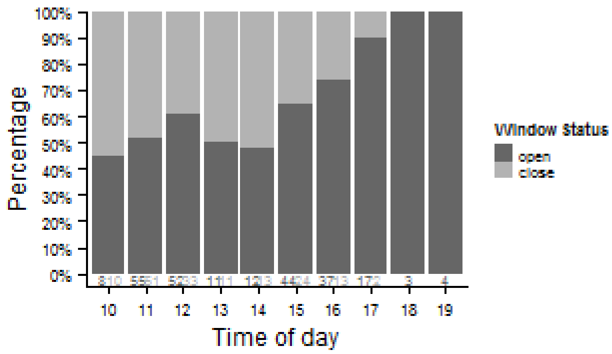

Figure 58. Percentage of window open in each hour of the day during summer in Jaipur.

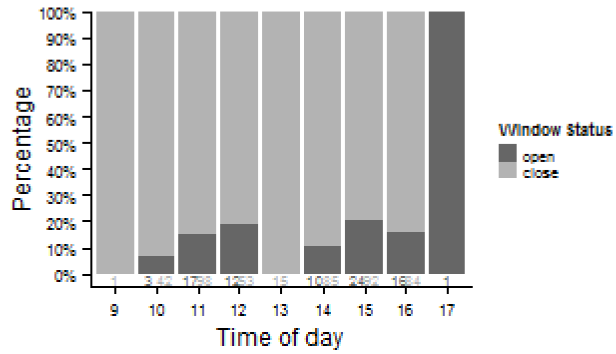

Figure 59. Percentage of window open in each hour of the day during winter in Jaipur.

Indoor and outdoor temperature are strongly related to window interaction. Figure 60 and Figure 61 show the percentage of window open per two degree bin of outdoor and indoor temperature respectively. As the outdoor temperature increases, the percentage of windows open in each bin increases. However, as the outdoor goes above 37 ˚C, percentage of windows open in each bin starts decreasing (Figure 60). This is probably because the warm outdoor air is not preferred inside the building even if it provides air movement. A similar behavior was observed in another study that was carried out in Hyderabad, which had a similar climate like Jaipur (Indraganti 2010). The percentage of windows open in each bin increased as the indoor temperature got warmer. Around 70% of the windows are open in every bin when the indoor temperature is between 31 – 39 ˚C (Figure 61).

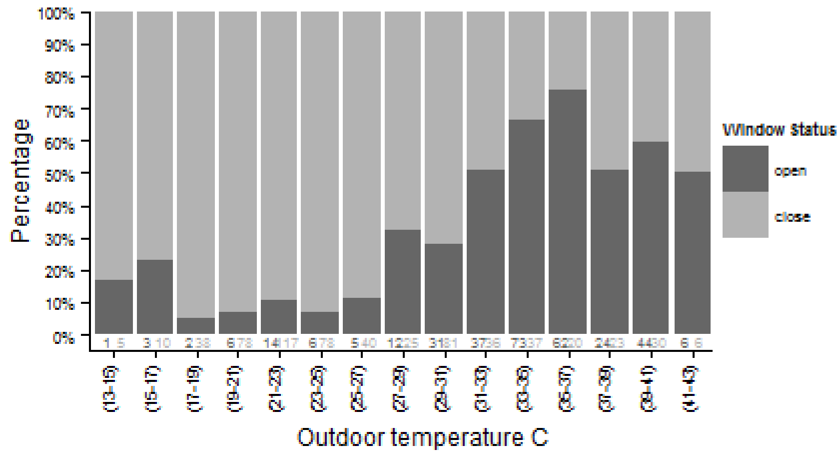

Figure 60. Window status with outdoor temperature in Jaipur.

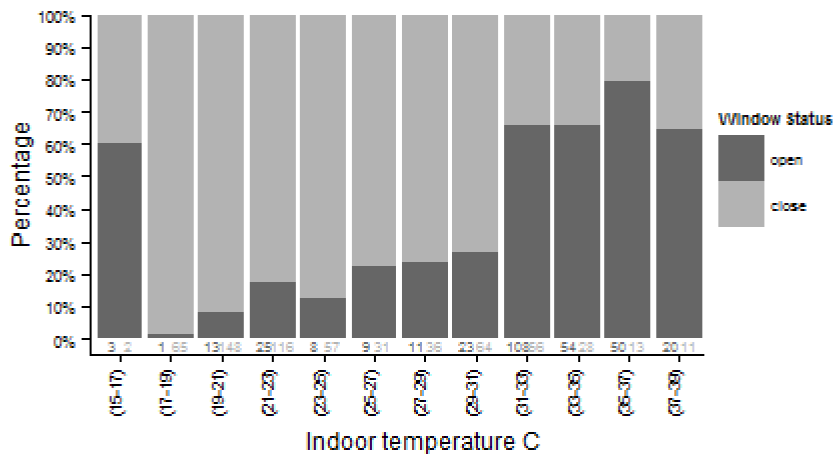

Figure 61. Window status with indoor temperature in Jaipur.

Based on the above potential predictor variables, a logit model is developed to predict window status in NV buildings in Jaipur. The levels of discrete variables such as time of day and season are the same as those in Alameda (Table 7). Since the percentage of open windows starts decreasing at outdoor temperatures above 37 ˚C, a second degree polynomial term for outdoor temperature is included in the model. The utility function is given in equation 6.

$$V_{open} = \left\{\left(\beta_{Tout} * Tout + \beta_{Tout} * Tout^2 + \beta_{Tdiff} * Tdiff + \beta_{AH} * AH + \beta_{EH} * EH + \beta_{summer} * Summer + ASC_{open}\right)\right\} \quad (6)$$

$$V_{close} = 0$$

The most significant variables that influence window status are outdoor temperature, difference between indoor and outdoor temperature and evening hour (Table 14).

Coefficient interpretation of significant variables in the window status model for Jaipur (Table 14)

- Coefficient of outdoor temperature is positive which corroborates the observation from Figure 60 that more windows are likely to be open as outdoor temperature increases.
- Coefficient of the difference between indoor and outdoor temperature is positive which means as the outdoors gets warmer than the indoors, it contributes negatively towards the probability of the window being open.
- Coefficient of evening hour is positive which means windows are most likely to be found open during evening hours compared to morning and afternoon.

Variable	**Coeff**	**Value**	**Std error**	**z value**	**p value**	
Tout	β_{Tout}	0.346	0.123	2.815	0.005	*
$Tout^2$	β_{Tout}	-0.003	0.002	-1.398	0.162	
Tin-Tout	β_{Tdiff}	0.209	0.039	5.329	<0.001	*
AH	β_{AH}	0.195	0.209	0.935	0.35	
EH	β_{EH}	0.705	0.253	2.785	<0.001	*
Summer	β_{summer}	0.566	0.304	1.861	0.063	
ASC_{open}	ASC_{open}	-8.423	1.823	-4.621	<0.001	*
Log-lik	-466.69					
AIC	947.39					
R_N^2	0.364					

Table 14. Coefficients of window status model for Jaipur.

Figure 62 shows the probability of a window being open in the afternoon during summer with the variation of outdoor temperature in Jaipur. The 50% probability of a window being open occurs at 29 ˚C. The shaded area represents the 95% confidence interval.

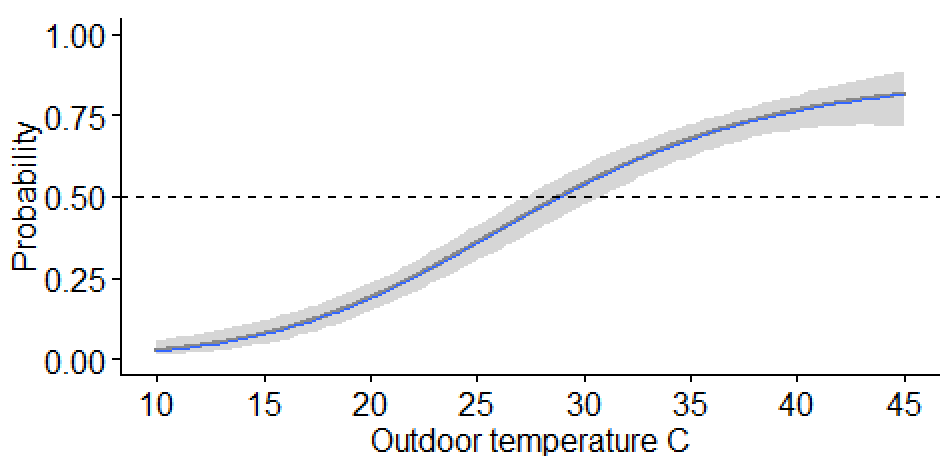

Figure 62. Probability of window being open with outdoor temperature.

4.3.4. Fan use in Alameda

Fans are not used very often in Alameda; overall at least one fan was on only during 8% of the occupied hour. This might be because the indoors don't get very warm and the air movement from opening the window is sufficient. To evaluate the temperature conditions when fans are used, Figure 63 shows the percentage of fan on per degree bin of indoor and outdoor temperature. The first predominant green colored bins appears at an outdoor temperature of 22 ˚C which means fans start getting turned on from 22 ˚C outdoors.

Figure 64 shows the fan status during the summer, winter and swing season. However, in the logit model evaluated later, the winter and swing season are merged together, a step similar to what was done for window modeling. The logit model needs a choice (fan being on) to be exercised at least once in all the levels of the explanatory variable. In Alameda, fans are off in all the observations during winter. At least one fan is on in 13 % of the work hour in summer and 8% work hour during swing (Figure 64). During summer there is a slight increase in the percentage of 'fans on' during evening hours (3 – 6 pm) compared to morning hours (10 am – 12 pm) (Figure 65). This might be because the warm indoor conditions occur during the evening hours in this building. Such a pattern is not seen during the swing season (Figure 66).

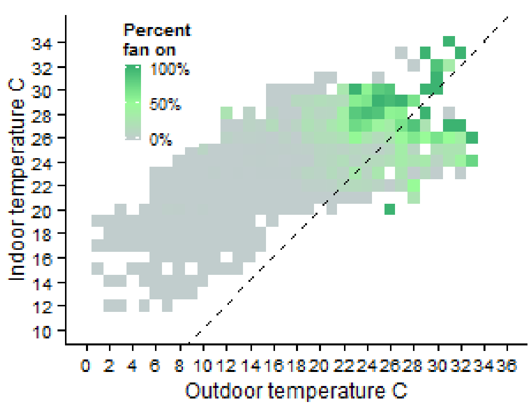

Figure 63. Percentage of fans 'on' binned per degree indoor and outdoor temperature in Alameda.

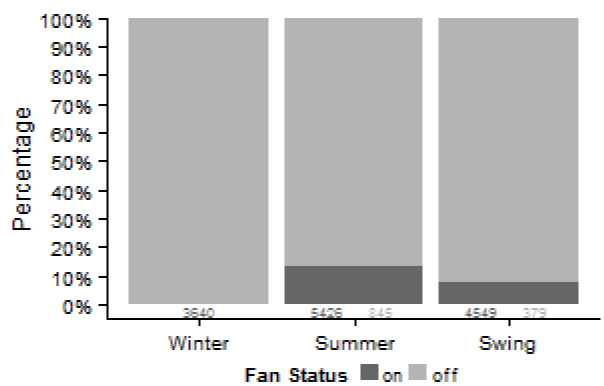

Figure 64. Percentage of fans 'on' in winter, summer and swing in Alameda.

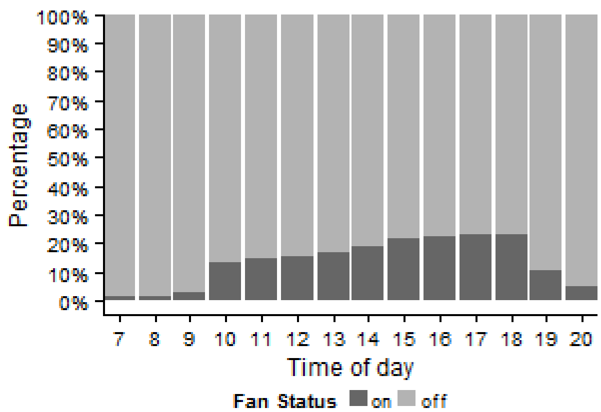

Figure 65. Percentage of fans 'on' at different hours of the day during summer in Alameda.

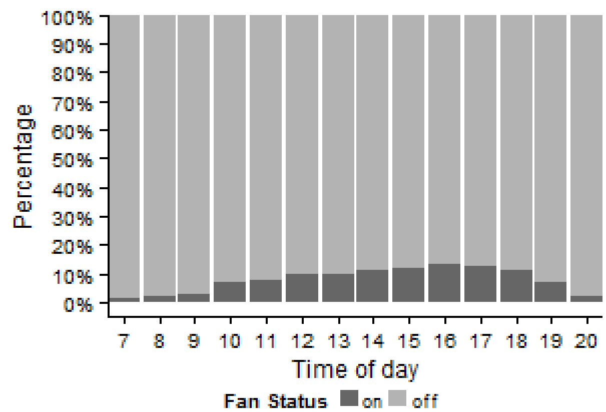

Figure 66. Percentage of fans 'on' at different hours of the day during the swing season in Alameda.

A logit model is fitted to predict the fan status based on the explanatory variables. The utility function for the choice situation is given in eqn 7 and summary of the coefficients is shown in Table 15. The regression results show that variables T_{out}, time of day (evening hour), summer and inertia significantly influence the fan status.

$$V_{on} = \{(\beta_{Tout} * Tout + \beta_{Tdiff} * Tdiff + \beta_{AH} * AH + \beta_{EH} * EH + \beta_{summer} * Summer + ASC_{on})\} \quad (7)$$
$$V_{off} = 0$$

Coefficient interpretation of significant variables in the fan status model for Alameda (Table 15)

- ASC_{on} is negative as expected which means a fan is likely to be off when all the parameters are zero.
- Coefficient of T_{out} is positive which means a fan is more likely to be turned on as outdoor temperature increases
- Coefficient of evening hour is negative, indicating that a fan is less likely to be found on during evening hour as compared to morning and afternoon hours of the day
- Coefficient of summer is negative which is counter intuitive. This might be possibly because fans are turned on during the swing as well
- Coefficient of inertia is positive as expected, which means if a fan is on in the previous hour there is a higher probability for fan to stay in the same state.

Variable	Coeff	Value	Std error	z value	p value	
T_{out}	β_{Tout}	0.253	0.033	7.628	< 0.001	*
$T_{in} - T_{out}$	β_{Tdiff}	-0.024	0.035	-0.697	0.486	
AH	β_{AH}	-0.233	0.156	-1.49	0.136	
EH	β_{EH}	-1.111	0.188	-5.914	< 0.001	*
Summer	β_{summer}	-0.386	0.139	-2.784	0.005	*
Inertia	$\beta_{inertia}$	3.129	0.086	36.31	< 0.001	*
ASC_{on}	ASC_{on}	-5.592	0.817	-6.847	< 0.001	*
R^2_N	0.789					
Log likelihood	-1108.30					

Table 15. Coefficients of the fan status model in Alameda.

Similar to the case of windows, the probability distribution of a fan being turned on with change in outdoor temperature is helpful in understanding the fan usage pattern. A logit model is fitted with only outdoor temperature as the explanatory variable and the coefficients are shown in Table 16. As expected, the ASC is negative while the coefficient of T_{out} is positive. When the outdoor temperature is 27.8 ˚C, there is a 50% probability of at least one fan being on (Figure 67).

Variable	Coeff	Value	Std error	z value	p value	
T_{out}	β_{Tout}	0.308	0.008	39.18	< 0.001	*
ASC_{on}	ASC_{on}	-8.56	0.179	- 47.84	< 0.001	*
R^2_N	0.34					
Log likelihood	-3050.99					

Table 16. Coefficients of the fan status model in Alameda with only outdoor temperature as predictor variable.

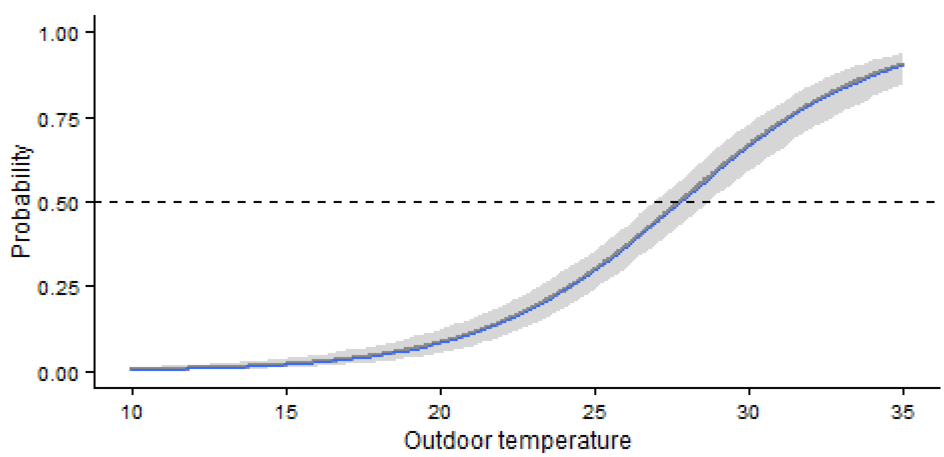

Figure 67. Probability of at least one fan being turned ‘on’ in Alameda.

4.3.5. Fan use in Jaipur

In a semi - arid climate like Jaipur, one of the key ways to be comfortable is by having elevated air movement. Ceiling fans provide the additional air movement especially when the air movement from opening windows is inadequate. Most of the NV case study buildings in the Jaipur study had ceiling fans and their usage pattern is characterized below.

Figure 68 shows the percentage of fans on per degree bin of outdoor and indoor temperature. Fans are turned on significantly when the outdoor temperature gets above 27 ˚C. Similar to the case of windows, there is no distinct indoor temperature at which fans start getting turned on (Figure 68). In summer, 99 % of the fans are on while in winter it is only 37% (Figure 69). Not surprisingly, in summer, the fans are on mostly all through the day (Figure 70) while in winter few of them get turned on during the late morning and afternoon hours (Figure 71).

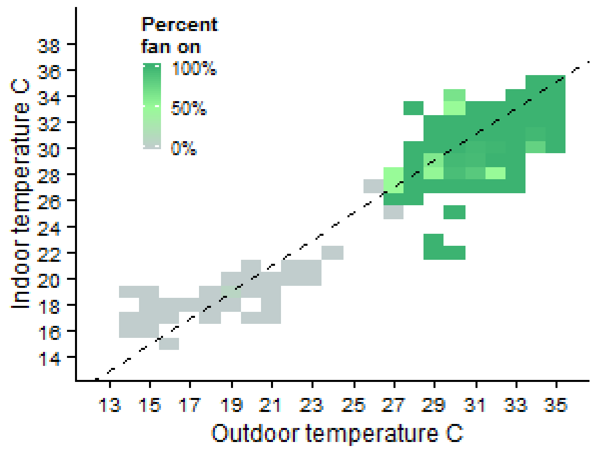

Figure 68. Percentage of fans on binned per degree indoor and outdoor temperature in Jaipur.

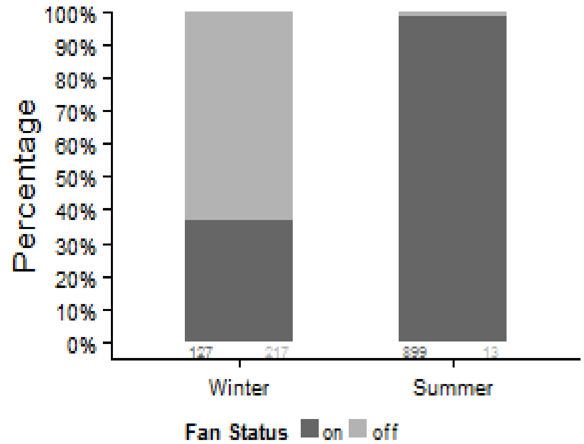

Figure 69. Percentage of fans on in summer and winter in Jaipur.

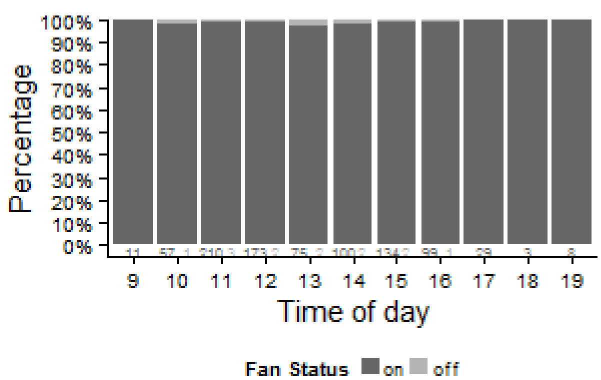

Figure 70. Percentage of fans on at different hours of the day during summer in Jaipur.

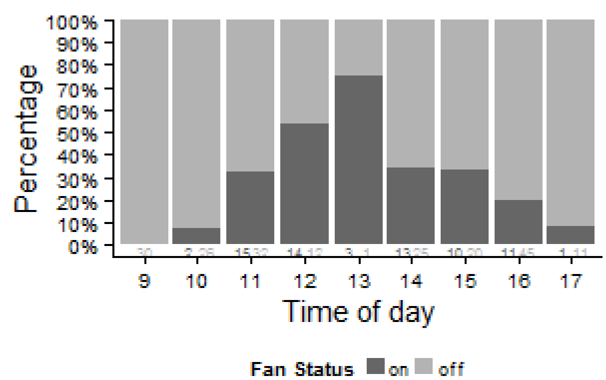

Figure 71. Percentage of fans on at different hours of the day during winter in Jaipur.

With the above variables as the potential explanatory variables for window opening, a logit model is estimated for predicting fan status in Jaipur. The utility function for the fan status is given in equation 8.

$$V_{on} = \{(\beta_{Tout} * Tout + \beta_{Tdiff} * Tdiff + \beta_{AH} * AH + \beta_{EH} * EH + \beta_{summer} * Summer + ASC_{open})\} \quad (8)$$
$$V_{off} = 0$$

The regression result shows that outdoor temperature, difference between indoor and outdoor temperature and summer are the significant variables (95% confidence interval) in predicting fan status. The R^2_N for this model is 0.79 which means that it is fitting the data very well.

Coefficient interpretation of significant variables in the fan status model for Jaipur (Table 17)

- Coefficient of Tout is positive which means fans are likely to be turned on as outdoor temperature increases.
- Positive coefficient of the difference between indoor and outdoor temperature means fans are more likely to be found on when the indoor temperature is warmer than the outdoor temperature.
- Coefficient of summer is positive which means the probability of a fan being switched on in summer is higher than winter.

Variable	**Coeff**	**Value**	**Std error**	**z value**	**Pr(>|z|)**	
Tout	β_{Tout}	0.418	0.042	9.901	<0.001	*
Tin-Tout	β_{Tdiff}	0.173	0.073	2.376	0.018	*
AH	β_{AH}	-0.573	0.324	-1.768	0.077	
EH	β_{EH}	-1	0.423	-2.365	0.018	*
Summer	β_{summer}	2.158	0.374	5.767	<0.001	*
ASC_{on}	ASC_{on}	-10.749	1.125	-9.551	<0.001	*
R^2_N	0.79					
Log likelihood	-180.25					

Table 17. Coefficients of the logit model for fan status in Jaipur.

Table 17 shows the coefficients of the logit model considering only outdoor temperature as the predictor variable. As expected, the ASC is negative while the outdoor temperature variable is positive. Interestingly, the R^2_N value is 0.75 which is quite high considering that only outdoor temperature is included in the model. The outdoor temperature at which there is a 50% probability of fan being 'on' is 26 ˚C. There is a steep rise in the probability when the outdoor temperature is between 23 – 30 ˚C. When the outdoor temperature goes above 30 ˚C, there is more than a 90% chance of a fan being on (Figure 72).

Variable	**Coeff**	**Value**	**Std error**	**z value**	**Pr(>|z|)**	
Tout	β_{Tout}	0.52	0.037	14.25	<0.001	*
ASC_{on}	ASC_{on}	-13.51	1.067	-12.66	<0.001	*
R^2_N	0.75					
Log likelihood	-211.3					

Table 18. Coefficients of the logit model for fan status in Jaipur.
(Only outdoor temperature as the explanatory variable)

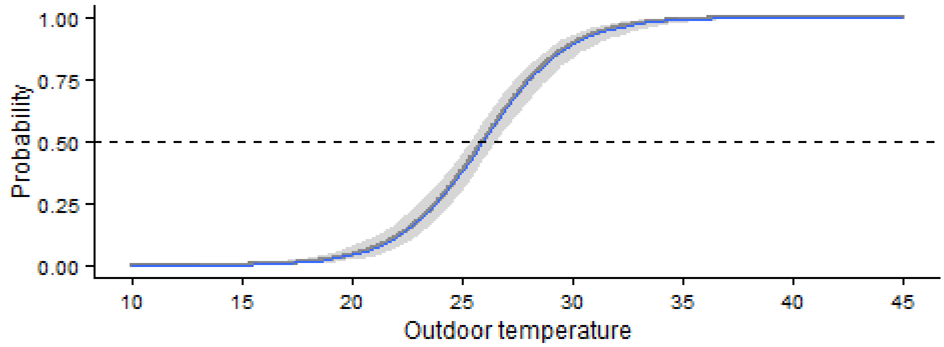

Figure 72. Probability of fan being turned on in Jaipur.

4.4. Discussion

The results from clothing, window adjustment and fan usage show that occupants in NV buildings interact with these adaptive opportunities driven by different variables. This finding is crucial because all these three adaptive opportunities are low cost methods of providing comfort and thus would have a substantial return on investment in both retrofits and new constructions.

Rigid dress codes and a narrow range of AC set points often restrict the clothing adaptation which the occupants would have made if the workspace had a flexible dress code and wider temperature range. For instance, the clothing results in this study show that during summer, occupants in Jaipur dress lighter with a mean clo value of 0.45 compared to Alameda with a mean clo value of 0.55. This is possibly because the mean outdoor temperature during summer in Jaipur is 32 ˚C, which is much warmer than the 20 ˚C summer mean outdoor temperature in Alameda. The difference in clo values could also be related to cultural factors; occupants in Jaipur very seldomly use accouterments in summer clothing as the temperature stays consistently warm throughout the day. On the other hand, accouterments in clothing such as a neck scarf or a thin jacket are often used in Alameda where the temperature fluctuates very often through the day even in summer. Another instance of adaptive clothing can be seen when the running mean outdoor temperature is less than 20 ˚C. Occupants in Jaipur dress heavier than those in Alameda in the same bin of outdoor temperature (Figure 50). This is possibly because in those bins, indoors is cooler in Jaipur than Alameda (Figure 51). This relationship between temperature and clothing adjustment is also crucial for both AC and MM buildings. For instance, in AC buildings in warm climates if the set points are maintained too low, occupants would feel cold because they have dressed light in response to the warm outdoor weather. This can give rise to a situation where occupants will start dressing heavier in summer to cope with cold indoor conditions; which needless to say is an inefficient way of providing comfort. Therefore, adequate attention should be given to fixing the set points so as to take advantage of the clothing adaptation.

Window opening results from Alameda and Jaipur show two different ways of modeling window interaction. The method of data collection in Alameda is longitudinal so it allows for a robust model that can identify idiosyncrasies in the explanatory variable. However, since the data is only from one building, the results cannot be extended to other buildings as it is. Jaipur data on the other hand is more representative of the local population because the data comes from multiple buildings and captures a diverse group of occupants.

The results from the Alameda analysis show that predictor variables like temperature, season and time of day influence each window differently. The difference exists predominantly at the room level. The back room windows are opened less compared to the front room. This could possibly be because the indoor temperature in the front room is warmer than the back (Figure 73). The reason why the temperatures are different is very likely because the front room has high internal load and more windows compared to the back room. The insulation location is just below the sheeting in the front room while it is at the bottom of the attic in the back room. The attic space acts as a buffer zone in the back room Figure 75. Another explanation for the windows being opened less in the back room compared to the front has to do with the ease of operation. Personal communication with one of the occupants from the Alameda building revealed that the back room windows were difficult to operate as compared to the front room windows.

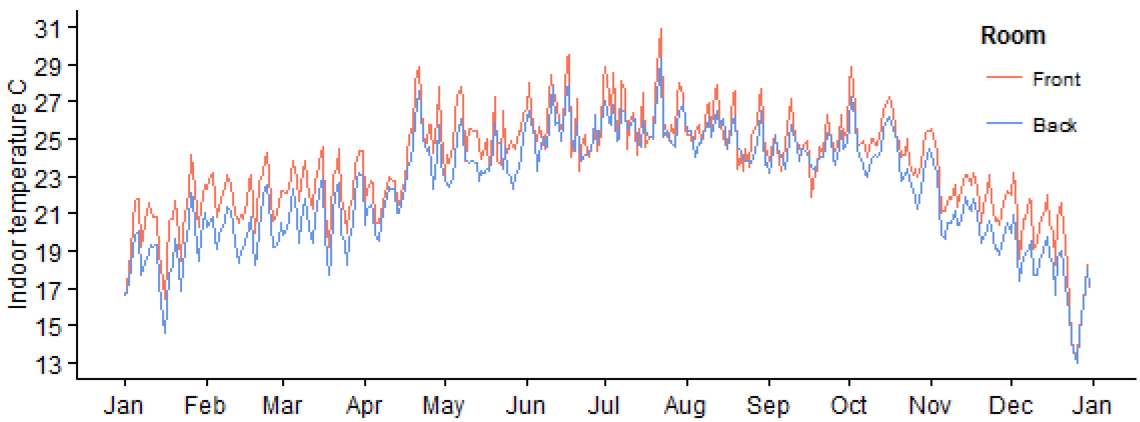

Figure 73. Daily mean temperature during occupied hours in the front and back room.

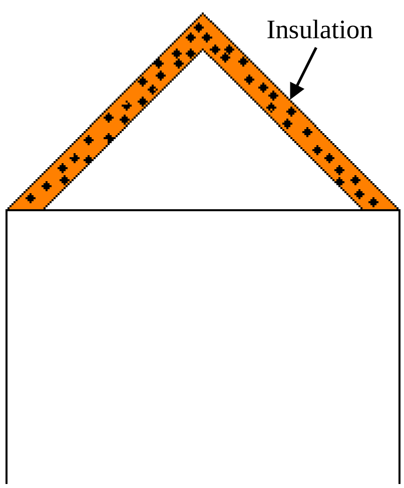

Figure 74. Insulation in the front room below the roof sheeting.

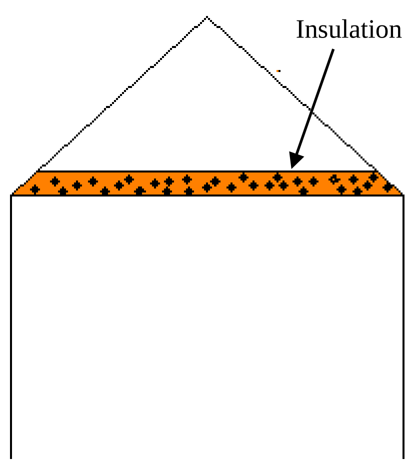

Figure 75. Insulation in the back room above attic.

In Alameda, the temperature difference variable (T_{in}-T_{out}) is not significant in predicting window status (Table 8) while in Jaipur it is significant (Table 14). The coefficient of temperature difference variable is positive for Jaipur which means that as the outdoor temperature gets warmer than the indoor temperature, fewer windows are likely to be open. Thus in a mild climate, outdoor temperature predicts window status well while in a hot climate, the difference between the indoor and outdoor temperature needs to be considered. This means that whether indoor or outdoor temperature is a better predictor of window status is climate specific.

In Alameda, windows are likely to be found open during morning hour compared to afternoon or evening while in Jaipur windows are more likely to be open in the evening hour compared to the other two times of the day. Windows are predominantly open in the morning in Alameda possibly because the room is stuffy when occupants arrive and they prefer to open the windows to bring in fresh air. Another possibility is that they are habituated to opening the window when they arrive in the morning. On the other hand in Jaipur, windows are open more during the evening hour likely because the outdoors are cooler than the indoors.

Fans are used more in Jaipur than Alameda; they are on in 99% of the work hour observations in Jaipur and only 13 % in Alameda. Moreover, there is a steep rise in the probability of a fan being ‘on’ in the outdoor temperature range of 25 – 30 ˚C in Jaipur as compared to Alameda (Figure 76). This could be because in Jaipur additional air movement from fans is needed to supplement the wind driven air movement from windows while in Alameda the natural air movement is sufficient.

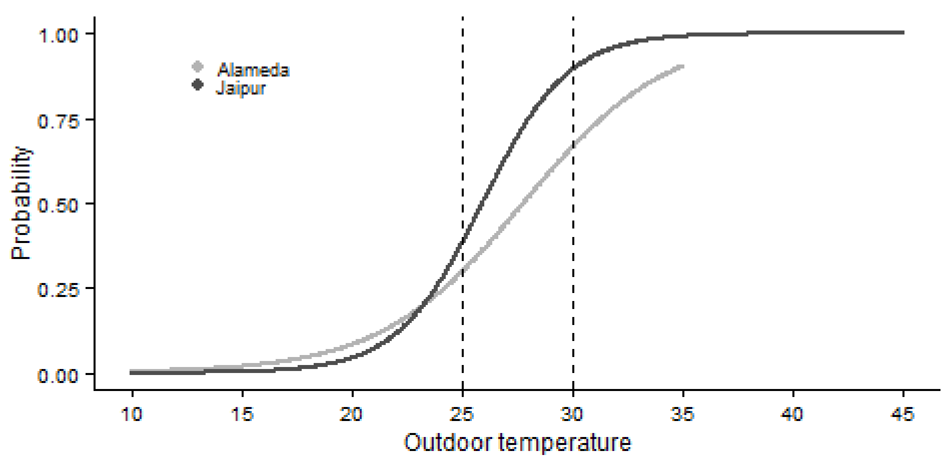

Figure 76. Probability comparison of a fan being ‘on’ at different outdoor temperature in Alameda and Jaipur.

Interestingly, temperature difference variable was not significant in predicting fan status in Alameda, but was significant in Jaipur. Outdoor temperature was significant in both the climates and had a positive sign. Both the results put together imply that fan operation is driven mainly by outdoor temperature in Jaipur while it is driven by both indoor and outdoor temperature in Alameda. It might be possible that fans in Alameda were not adjusted based on indoor temperature because it did not get too warm indoors. Since fans are fast acting and provide an instant cooling effect, they were not needed in the mild conditions. On the other hand in Jaipur, indoor temperature was a driver for fan interaction because the indoors got sufficiently warm at times and air movement from fans was very much needed.

The relevance and advantages of all these results for existing buildings is in retrofitting the workspace to have operable windows and air movement by ceiling/movable fans. It also calls for a radical shift in work cultures where rigid dress codes give way to a flexible dress code that is driven mainly by climate and comfort. For new buildings, these results are an illustration of occupants' adaptive actions in existing NV buildings. Designers can look to these buildings as precedents for natural ventilation and ensure that occupants are given opportunities to exercise these adaptive actions in the buildings that are yet to come.

Chapter 5: Thermal comfort in NV buildings

5.1. Introduction

Thermal comfort is defined as the condition of mind which expresses satisfaction with the thermal environment (ANSI/ASHRAE 2013). This definition itself indicates that thermal comfort is a subjective evaluation of the thermal condition by the occupant and it would vary significantly across individuals. Occupants' thermal comfort opinion is partly influenced by past memories one has had in a space while some of it is be due to the present thermal conditions. Expectations also play a key role in determining whether or not the indoor conditions are comfortable. For example, people who have grown up in warm climates without air-conditioning are very likely to be more accepting of warm conditions than those who have lived in mild climates. Some other factors that have been proposed to influence occupants thermal comfort opinion are flexible dress codes, access to windows and fans, connection to the outdoors, and variable indoor environmental factors such as temperature and air movement (Brager and de Dear 1998).

In 1978, an adaptive comfort theory was proposed by Humphreys which aimed at providing a quantitative relationship between the indoor and outdoor temperature in NV buildings (Humphreys 1978). The main hypothesis of the adaptive theory was that occupants in NV building are comfortable in a wider range of indoor temperatures if they have flexibility in clothing and have access to controls such as windows and fans. Applicability of this theory in practice was greatly bolstered by the work done by de Dear and Brager in the ASHRAE RP-884 project in 1998 (de Dear and Brager 1998) and by Nicol et.al. in the SCATs project in the year 2002 (Nicol and Humphreys 2002). The RP-884 project analyzed a dataset of thermal comfort field studies over 4 continents and proposed a relationship between indoor comfort temperature and mean monthly outdoor temperature which is also known as the ASHRAE standard 55 adaptive model (ANSI/ASHRAE 2013). The SCATs project also proposed a similar relationship, but it had running mean temperature (weighted daily mean temperature for past 7 days) on the x-axis instead of mean monthly temperature. The adaptive model developed from the SCATs project is included in the EN15251 standard (Nicol and Humphreys 2010).

Other than these two projects that analyzed large databases, numerous chamber and field studies have independently evaluated thermal comfort in mild and hot climates. One of the early comfort experiment in India was done by Sharma and Ali in 1986. They conducted a chamber study of 18 subjects in three consecutive summers and derived a 'tropical summer index' which gave a relationship between comfort and environmental parameters. Air velocity was found to be a key variable that kept occupant comfortable at indoor temperatures as high as 33 ˚C (Sharma and Ali 1986). A chamber study in Thailand of 183 male and 105 female subjects that aimed to quantify effect of air velocity on neutral temperatures also concluded the same. When indoor temperature was at 28 ˚C air velocity greater than 0.2 m/s provided comfort. Neutral temperature went as high as 35 ˚C when air speed was between 2-3 m/s at humidity less than 60% (Khedari 2000) .

Although chamber studies have been widely used for thermal comfort studies, they have a major limitation since they don't fully represent the real building scenario. For instance in naturally ventilated buildings, the PMV index, overestimates thermal sensation especially in warm conditions (Feriadi and Wong 2004). A study done in Shanghai, China with 1814 office workers found that the actual mean vote was 0.64 times the PMV (Ji 2006). McIntyre in his paper titled 'Chamber studies – Reductio ad Absurdum?' argues that this is mainly because the chamber studies disregard the ill-understood factors that affect comfort. PMV index was developed from one such set of chamber studies (McIntyre 1982).

In the past 20 years, many field studies have been carried out in office and residential buildings (de Dear 2013). Most of them quantified clothing levels in summer and winter and the use of adaptive control such as windows, fans and blinds. They also calculated the neutral temperatures and compared it with ASHRAE standard 55, EN15251 or other adaptive models. As one example in a hot climate, surveying 1100 office workers in Bangkok, Busch found that the comfort temperature in NV buildings was 31 ˚C in NV buildings and 28 ˚C in AC buildings (Busch 1992). Busch also discussed the subjective nature of thermal comfort and on evaluating the relationship between acceptability and preference metrics, he found preference to be a stricter metric than acceptability. In a similar warm climate of Bangladesh, comfort temperatures ranged between 24 – 33 ˚C. Moreover, the tolerance to humidity was high and people voted to be comfortable when humidity was above 95% (Mallick 1996).

Comfort studies in residential buildings have shown results similar to office buildings; occupants are comfortable in a wider range on indoor temperature. Feriadi and Wong conducted a study in 274 NV houses in Jogjakarta Indonesia to evaluate comfort, adaptive model and behavioral actions. The neutral temperature was 29.17 ˚C and preferred temperature was 26 ˚C. However, whether or not occupants are comfortable depends on the metric. This study found that occupants voted stringently with thermal sensation as compared to when asked directly about comfort. 78% voted opening window as the most preferred adaptive action followed by getting more drink and changing clothes. The least favored alternative was operating AC. Most of these houses did not have AC and even if they did, it was expensive to run it for a long time (Feriadi and Wong 2004).

The findings from all these field studies are aimed to aid design of low energy buildings. However, in countries where most of the buildings have already been built, the question becomes how passive design retrofits can be done in order to save energy while providing comfort. Barlow and Fiala, in a study done in UK found that occupants voted opening windows as the most preferred adaptive opportunity after the office was retrofitted with new windows and NV grilles (Barlow and Fiala 2007). Another example of a retrofit study is the development of an adaptive comfort algorithm by McCartney and Nicol (McCartney and Nicol 2002). They implemented the comfort temperatures derived from field study into the HVAC control system of the building. Significant energy saving was reported with no reduction in comfort. (Ackerly and Brager 2012)

The key point that stands out from this literature review is that occupants especially in warm climates are comfortable at warmer temperatures. However, the upper limits of comfort need to be carefully evaluated in order to be able to take the best advantage of adaptation while designing the buildings that are yet to be constructed. This implies that the metrics used to determine thermal comfort such as thermal sensation, acceptability and comfort need to be evaluated holistically.

Thermal comfort results from Alameda are compared to Jaipur in order to evaluate the thermal adaptation occurring in both climates. The difference in outdoor temperature is such that the winter conditions in Jaipur overlap with summer conditions in Alameda. The relationship between indoor comfort temperature and running mean outdoor temperature in both the climates is derived and compared with the ASHRAE standard 55 adaptive chart. Thresholds of indoor comfort temperature are derived and the relationship between metrics of satisfaction between both the climates is explored.

5.2. Analysis method

5.2.1. Linear regressions

Thermal comfort modeling in this chapter is done mainly by using linear regression and partly by using logit regression; the theory of logit regression was explained in section 4.2.1. Linear regression is a simple method of establishing a relationship between response variable(s) and explanatory variable(s). The linear equation of a single explanatory variable is given by

$$y = a + bx$$

Where ‘y’ is the response variable, ‘x’ is the explanatory variable, ‘b’ is the coefficient of the regression and ‘a’ is the intercept.

The correlation between variables is given by the R – value and the percentage of variance in the response variable that is explained by the explanatory variable is shown by the R-squared (Moore and McCabe 1999). However, whether or not a variable is significant in predicting the response variable is determined by a t-test. This involves making a null hypothesis and testing it against and alternative hypothesis. The probability computed assuming the null hypothesis is true is known as the p – value. Lower the p – value, stronger is the evidence provided by the data (Moore and McCabe 1999).

5.3. Results

5.3.1. Thermal sensation and comfort in NV buildings

Histogram of TS and comfort (Alameda/Jaipur)

Occupants in Alameda vote in the three central categories of the thermal sensation scale - “slightly cool”, “neutral” or “slightly warm” - in 94% of the observations while in Jaipur they do so in 77% of the observations. A striking difference is that majority of the occupants in Alameda vote in the “neutral” category while those in Jaipur vote equally in all the three categories (Figure 77).

In addition to thermal sensation, thermal acceptability and thermal comfort are two other metrics that are used to evaluate occupants’ thermal opinion. The Alameda study asked the question- “Right now how acceptable is the temperature at your workplace?” and the Jaipur study asked- “Based on temperature, humidity and air movement how comfortable do you feel right now in your workplace?” Results show that occupants in Alameda vote to be acceptable of their environment in 98% of the observations. Out of this 98%, 54% found the temperature to be very acceptable (Figure 78). In Jaipur, the scale was different but, for comparison, we are assuming that any of the votes on the comfortable side of the scale are equivalent to acceptable. Occupants vote to be "slightly comfortable", "comfortable" or "very comfortable" in 87 % of the observations (Figure 79). This result from Jaipur is particularly interesting because the indoor temperatures is in the range of 20 – 39 ˚C during summer (See previous Figure 27). Corroborating the adaptive comfort theory, it is evident that occupants in the NV buildings are comfortable over a wider range of indoor temperature than the range of 19 – 27 ˚C defined by the PMV based model.

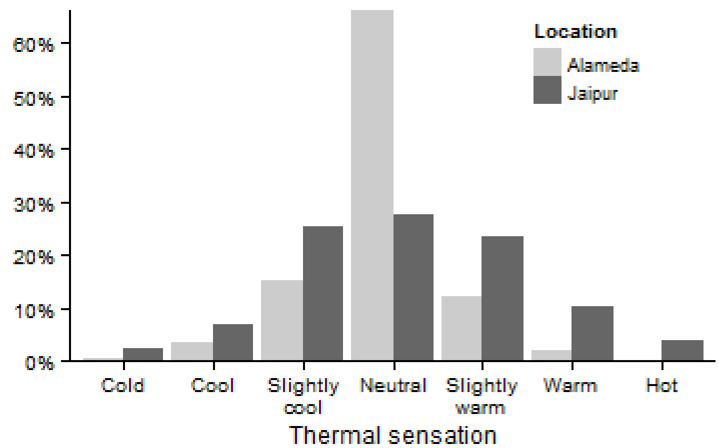

Figure 77. Thermal sensation distribution in Alameda and Jaipur.

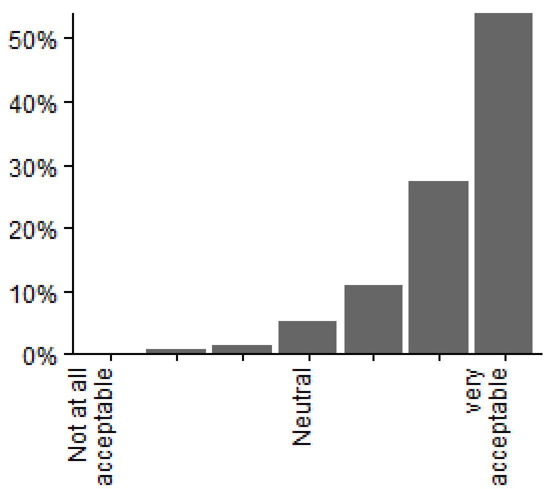

Figure 78. Acceptability votes in Alameda.

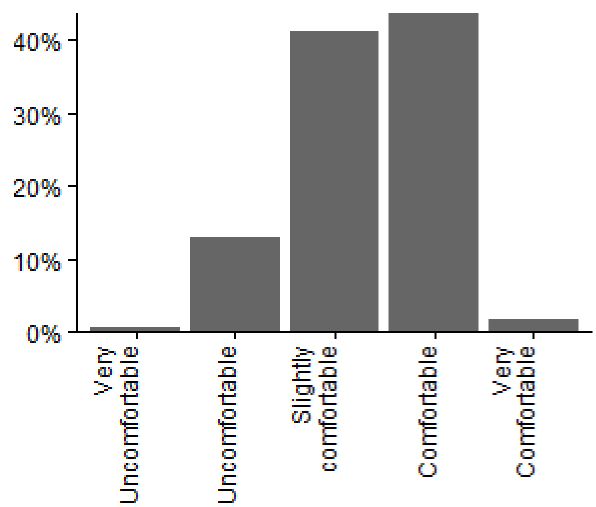

Figure 79. Comfort votes in Jaipur.

Relationship between indoor temperature and thermal sensation

Indoor temperature is one of the key variable that influences thermal comfort. Figure 80 shows the thermal sensation vs indoor temperature boxplot for Alameda and Jaipur. The two dotted lines at ± 1 shows "slightly warm" and "slightly cool" thermal sensations and the dark red dot is the mean. Observations from both the climates overlap in five of the indoor temperature bins. For the same indoor temperature range, especially between 26 – 29 ˚C, thermal sensation of the occupants from Jaipur is significantly cooler ($p<0.05$) than those from Alameda. Significance is shown by a red star just above the number of votes in Figure 80. This could be very likely because the Jaipur buildings had high air movement. Fans were on most of the time in Jaipur and they also got turned on at lower outdoor temperatures compared to Alameda (Figure 76). Another explanation for the difference in thermal sensation is that Jaipur is predominantly a hot climate and occupants have physiologically or psychologically adapted to the warm conditions. In other words, having experienced hot indoors of 35- 38 ˚C, occupants in Jaipur feel the indoor temperature between 26 – 29 ˚C to be cooler than occupants from Alameda who don't experience indoor temperatures above 26 – 29 ˚C.

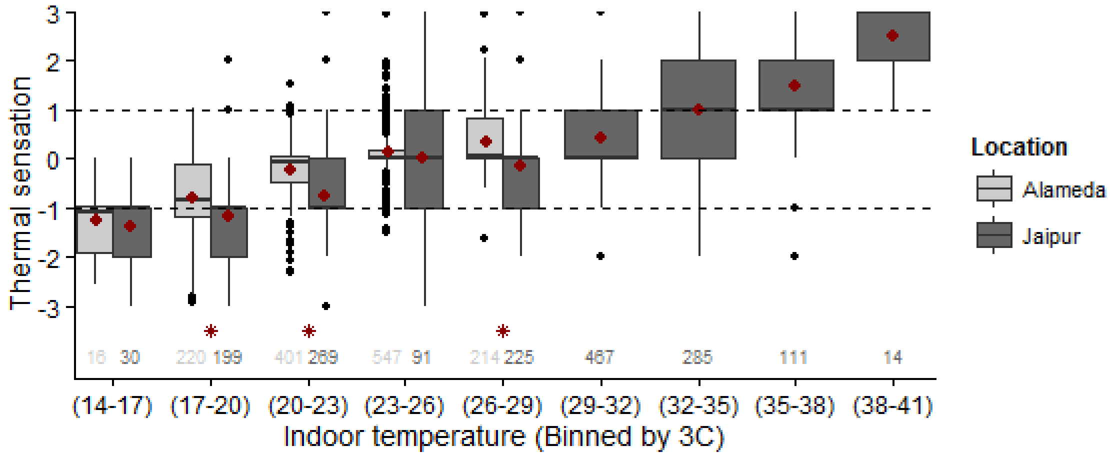

Figure 80. Thermal sensation variation with indoor temperature.

Correlation between thermal comfort variables from Alameda and Jaipur

Correlation between variables is done to evaluate the variables that might influence comfort and thermal sensation. Figure 81 shows the correlation matrix for Alameda and Figure 82 for Jaipur. Air velocity variable is included only for Jaipur because the Alameda study did not record indoor air speed. In Alameda, acceptability does not correlate strongly with any variable, which is counter intuitive. Thermal sensation on the other hand correlates with indoor and running mean outdoor temperature (R = 0.52 and 0.4 respectively). In Jaipur, the comfort variable does not strongly correlate with any of the other variables (Figure 81). Thermal sensation is correlated with indoor temperature, running mean outdoor temperature and air velocity (R = 0.65, 0.54 and 0.46 respectively). It is interesting to note that thermal sensation correlates with indoor temperature more than outdoor temperature in both the climates. The low correlation of "acceptability" and "comfort" variables with other variables might be because both of them are more subjective in nature than thermal sensation, and thus are influenced by parameters that were not recorded in the study.

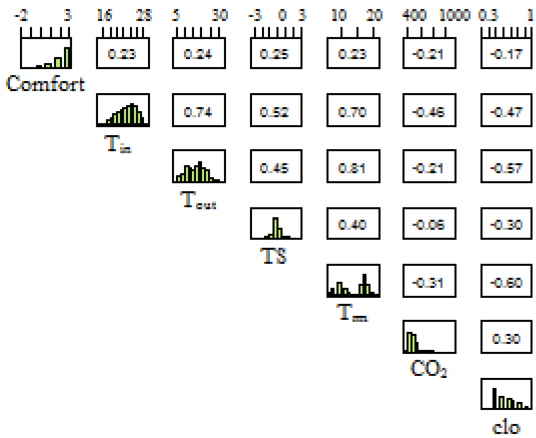

Figure 81. Correlation between variables influencing comfort in Alameda.

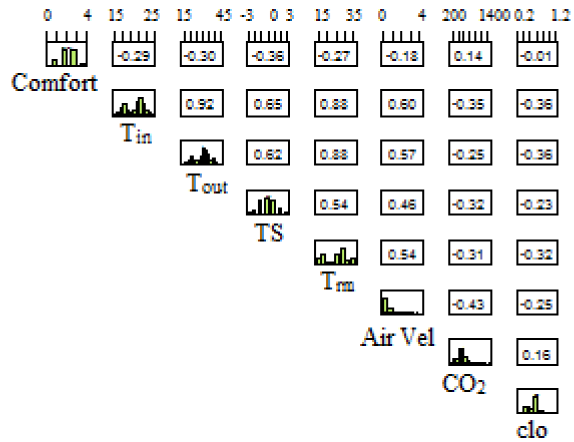

Figure 82. Correlation between variables influencing comfort in Jaipur.

Linear regression model for thermal sensation

From the correlation matrix, the main variables correlating with thermal sensation are selected to develop a linear regression model of thermal sensation. The R-squared values for a linear regression model between thermal sensation and a combination of different explanatory variables are shown in Figure 83 for Alameda and Figure 84 for Jaipur. Adding variables other than indoor temperature did not increase the R-squared by much. In Alameda, the R-squared increased from 0.17 to 0.18 when all the parameters were included in the model in addition to indoor temperature (Figure 83) while in Jaipur, it increased from 0.39 to 0.41 (Figure 84). This shows that amongst all variables, indoor temperature captures to a large extent the variation in thermal sensation. Thus in the interest of reducing the complexity of the model, linear regressions are fitted between thermal sensation and only indoor temperature for summer and winter season in Alameda and Jaipur.

Coefficients of the regressions are shown in Table 19. It is interesting to note that during summer, the neutral temperature (indoor temperature at which an occupant votes to have a thermal sensation ‘0-Neutral’) in Jaipur is 6 ˚C higher than Alameda (Table 19). The average running mean outdoor temperature in Jaipur during summer is 12.5 ˚C warmer than Alameda. This difference is aptly explained by the clothing levels and air movement values observed in both the locations. As noted in the clothing adaptation section 4.3.1, occupants in Jaipur dressed lighter than those in Alameda during summer with a mean clo value of 0.45 compared to 0.55. In the Jaipur buildings, the indoor air speed was above 0.5 m/s for most of the observations which according to ISO 7730 can be equivalent to a temperature drop of 3 ˚C (ISO 7730 - 1994). During winter, the neutral temperature in Jaipur is 2 ˚C higher than Alameda which can also be explained by the physical factors and adaptation to outdoor temperature conditions. The average running mean outdoor temperature in Jaipur is 10 ˚C warmer than Alameda in winter. Since the winter temperature in Jaipur did not go as low as Alameda and were interspersed with warm days, occupants in Jaipur dressed lighter than those in Alameda in this season. However, the summer adaptation can be observed more distinctly than the winter adaptation.

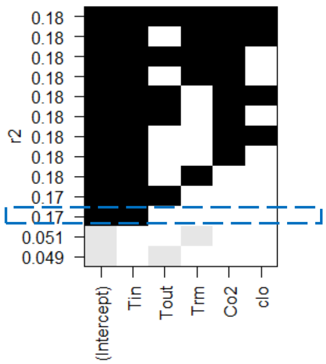

Figure 83. R squared value for different combination of parameters in Alameda.

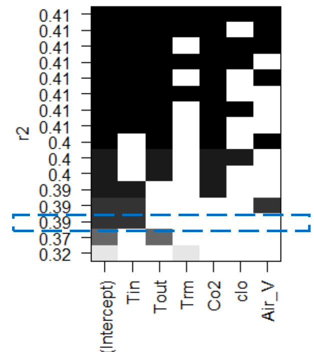

Figure 84. R squared value for different combination of parameters in Jaipur.

Location-Season	Regression equation	R^2	p value	Neutral temperature ˚C	Average running mean temperature ˚C
Alameda- Summer	TS = 0.15 Tin – 3.44	0.136	<0.001	22.9	17.3
Jaipur- Summer	TS = 0.24 Tin – 6.92	0.262	<0.001	28.8	29.8
Alameda- Winter	TS = 0.15 Tin – 3.66	0.24	<0.001	24.4	9
Jaipur- Winter	TS = 0.16 Tin – 4.22	0.29	<0.001	26.4	18.7

Table 19. Coefficients of linear regressions between thermal sensation and indoor temperature.

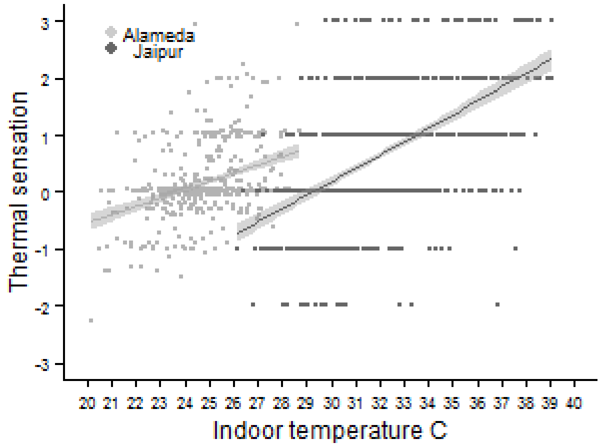

Figure 85. Thermal sensation variation with indoor temperature during summer.

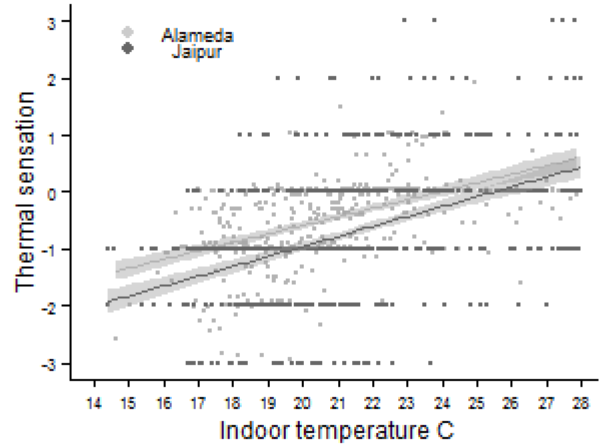

Figure 86. Thermal sensation variation with indoor temperature during winter.

Metrics of comfort

Thermal sensation is the commonly used metric for evaluating comfort. ASHRAE standard 55 defines the 80 and 90% satisfaction zone based on the associated thermal sensation band of ± 0.85 and ± 0.5, taken from the PMV-PPD curve. The thermal sensation band for 80% satisfied corresponds to thermal sensation votes between "slightly cool" to "slightly warm". The main reason for choosing thermal sensation as the metric for satisfaction was because many field studies did not ask questions with more direct metrics such as "thermal acceptability" or "thermal comfort".

The Alameda study asked about "right now acceptability with temperature" while the Jaipur study asked "right now comfort opinion, taking into consideration temperature, humidity and air velocity". Evaluating this relationship between thermal sensation and indoor temperature is important from the adaptation perspective. For instance, an occupant might vote to be feeling "slightly warm" but is acceptable or even comfortable with the temperature conditions. Thus the goal here is to see if people are satisfied with conditions that drift from neutrality.

Figure 87 shows the percent voting to be "acceptable" for every combination of thermal sensation and indoor temperature in Alameda. A green colored tile means more than 80% vote to be acceptable in that bin. Figure 88 shows the same information (percent voting comfortable for each combination of thermal sensation and indoor temperature) for Jaipur and the only difference is that the metric is "comfort". Only those bins with at least 5 votes are shown.

In Alameda, occupants are acceptable of the indoor temperature even when their thermal sensation is away from neutrality (Figure 87). A similar pattern is observed in Jaipur but with some restraint (Figure 88). For indoor temperatures in the range of 17 - 34 ˚C, occupants who vote their thermal sensation between "cool" to "slightly warm" are comfortable in Jaipur. When the indoor temperature is greater than 29 ˚C, occupants who feel "warm" or "hot" are uncomfortable. This shows that, in Jaipur, discomfort on the warm side starts at a thermal sensation of being "warm". It is interesting to note that at indoor temperatures above 35 ˚C, occupants who vote to be "slightly warm" are also uncomfortable. This might be very likely because this is a dry climate and there is not enough heat loss from the body due to evaporation. The air movement is also ineffective because of the high temperature.

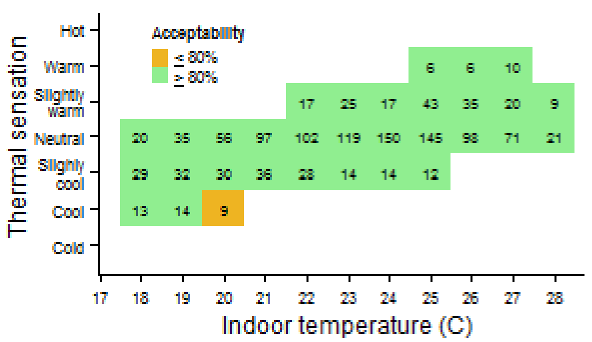

Figure 87. Percentage voting to be acceptable per degree indoor temperature and thermal sensation in Alameda.

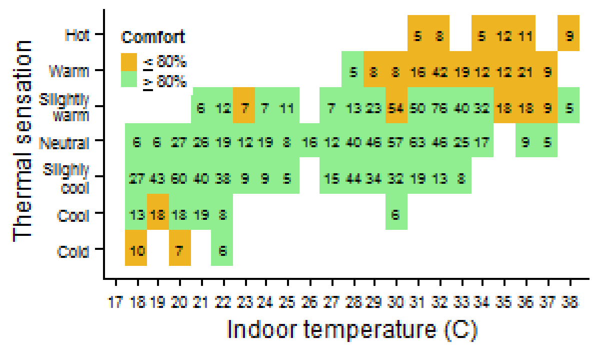

Figure 88. Percentage voting to be acceptable per degree indoor temperature and thermal sensation in Jaipur.

Comfort zone

The ASHRAE Standard 55 adaptive comfort model was developed from a dataset consisting of thermal comfort field study data from different continents. Although field studies from Alameda and Jaipur were not included in the RP-884 dataset, there were other cities that were emblematic of the Alameda climate such as other locations in the bay area in California and the UK. The climates similar to Jaipur were cities from Australia and Pakistan. To compare the predictions of the ASHRAE adaptive model, the field study observations from Alameda and Jaipur are overlaid on the ASHRAE adaptive chart (Figure 89 and Figure 90). For better visualization, the data is binned per degree indoor and running mean temperature. Only those bins with five or more votes are shown. Green color means more than 80% are satisfied in that particular bin and gold means less than 80% are satisfied.

In Alameda, 76% of the observations (1065 out of 1408) are within the range where the adaptive model is applicable (running mean temperature between 10 – 33 ˚C) while in Jaipur it is 90% (1531 out of 1691). For those votes that lie within the 80% satisfaction line, occupants vote to be comfortable in 98% of the observations in Alameda and 94% in Jaipur. In Alameda, there are 343 observation that occur when the running mean temperature is less than 10˚C. Occupants vote to be comfortable 97 % of the time in those conditions. Another interesting result is seen in Jaipur from Figure 90, when the indoor temperature is above the 80% comfort line on the warmer side and running mean temperature is less than or equal to 33 ˚C. Occupants vote to be “slightly comfortable” or “comfortable” 83% of the time. This shows that ASHRAE comfort model does a good job of predicting comfort within the 80% comfort zone in both mild and semi-arid climates. However, the model needs to be updated further to predict the comfort conditions when the running mean temperature is below 10 ˚C. For semi-arid climates, the thresholds of indoor comfort temperature need to be modeled independently for that particular climate.

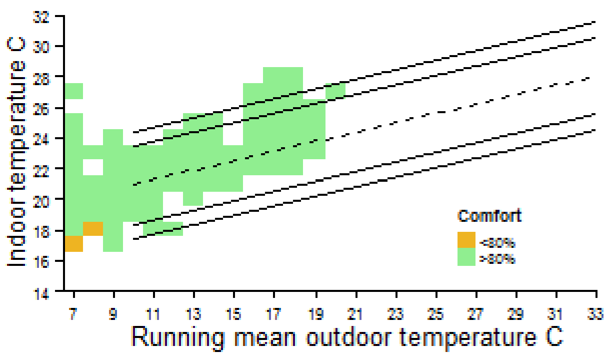

Figure 89. Percentage comfortable based on indoor temperature and running mean outdoor temperature in Alameda

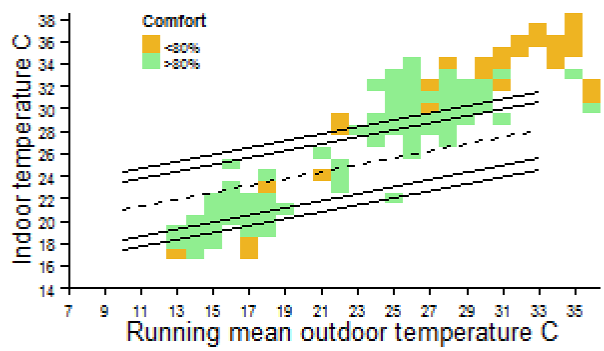

Figure 90. Percentage comfortable based on indoor temperature and running mean outdoor temperature in Jaipur.

Comfort model and thresholds of comfort

The ASHRAE standard 55 adaptive model was developed from a large database collected during the ASHRAE RP-884 project. Neutral temperatures per building per season was calculated and a linear regression was done between these neutral temperatures and the mean monthly outdoor temperature to get the neutral temperature line (Figure 91). The 80 and 90 % satisfaction lines were then derived by adopting the relationship between mean thermal sensation and % satisfaction from the PMV-PPD charts: ± 0.5 for 90% satisfaction and ± 0.85 for 80% satisfaction. However, the 2010 addendum of the ASHRAE standard 55, allows for a provision to take into account elevated air movement that results in a 2K increase in the operative temperature on the warmer side compared to the current standard (ANSI/ASHRAE 2010b).

There are three main drawbacks with this method

- Calculating neutral temperature per building is not possible if there aren’t sufficient buildings in the dataset.

- Averaging the thermal sensation data per buildings leads to a loss of information that is inherent in the individual votes.
- Mean thermal sensation between ± 0.5 and ± 0.85 may not be the appropriate thresholds for thermal comfort in a particular context.

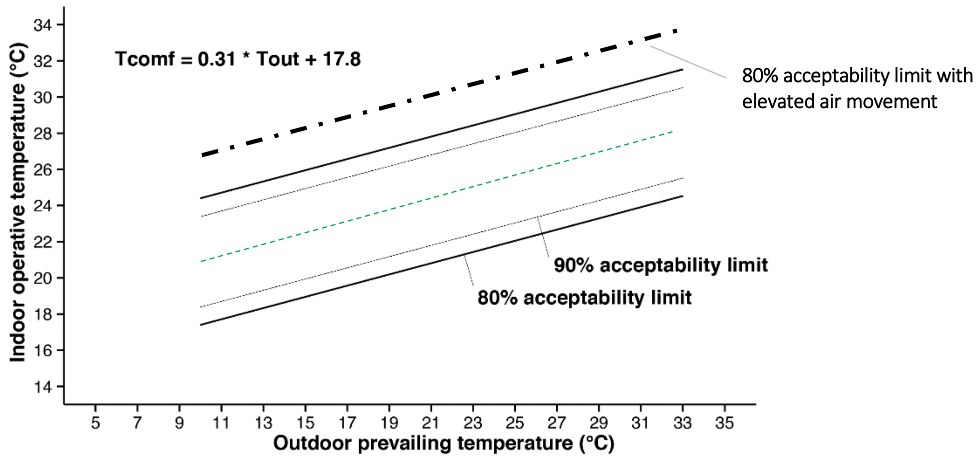

Figure 91. ASHRAE standard 55 adaptive chart.

Considering these drawbacks in the modeling method of ASHRAE standard 55, a different approach is proposed. The Alameda study asked an acceptability question while the Jaipur study asked about comfort. These two metrics are more direct representations of thermal comfort opinion than thermal sensation. Figure 92 shows the indoor temperature and running mean outdoor temperature for Alameda only during those times when occupants voted that the indoor temperature was acceptable. The same is done for Jaipur in Figure 93, but the metric is comfort. The regression blue line, which can be called as the 'comfort line', is also shown. The slope of this comfort line is slightly steeper than the ASHRAE standard 55 neutral temperature line in Alameda and is much steeper in Jaipur.

The next question that follow is how far we can go from this comfort line? Two separate logits models are fitted to the difference between indoor temperature and comfort temperature for warm dissatisfaction and cold dissatisfaction. Warm and cold dissatisfied votes are derived from the "acceptability" and "thermal sensation" combination in Alameda, and the "comfort" and "thermal sensation" combination in Jaipur. For instance in Alameda, an occupant who votes to be "unacceptable" and has a thermal sensation greater than or equal to +1 is flagged to be "warm dissatisfied" and an occupant who votes "unacceptable" and had thermal sensation less than or equal to -1 is flagged to be "cold dissatisfied". A similar approach is repeated for Jaipur with "comfort" as the metric. The probabilities of being warm and cold dissatisfied are then added to get the total probability of being dissatisfied (Figure 94 and Figure 95). Coefficients of the logit model are shown in Table 20.

In Alameda, the indoor conditions did not get very far away from comfort so as to cause discomfort. Thus, there is no clear threshold on the warm side. On the cool side, 80% occupants are acceptable even if the indoor temperature goes 5.5 ˚C below comfort temperature. In Jaipur, 80% comfort is achieved if the indoors are maintained within 4˚C above the comfort temperature on the warm side. On the cool side, 80% comfort is achieved up to when the indoor temperature is 9 ˚C below the comfort temperature. The range on the cool side is wider than that on the warm side.

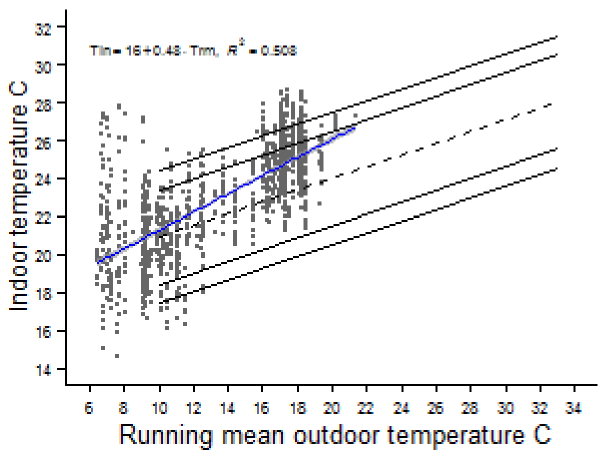

Figure 92. Regression equation based on acceptability in Alameda.

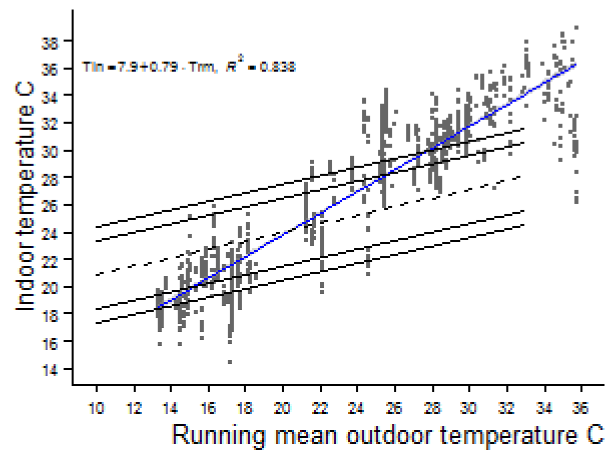

Figure 93. Regression equation based on comfort in Jaipur.

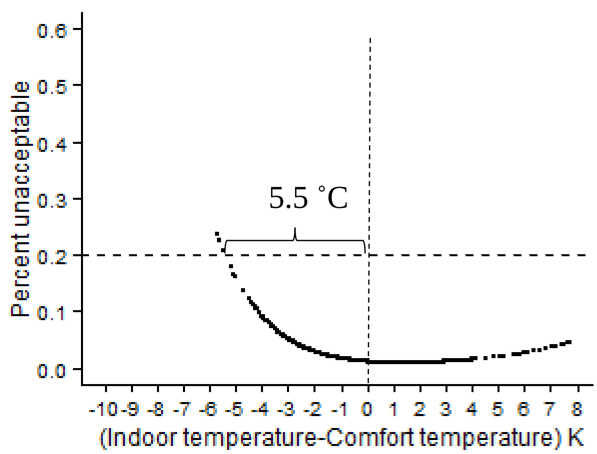

Figure 94. Percent uncomfortable with variation of indoor temperature from comfort temperature in Alameda.

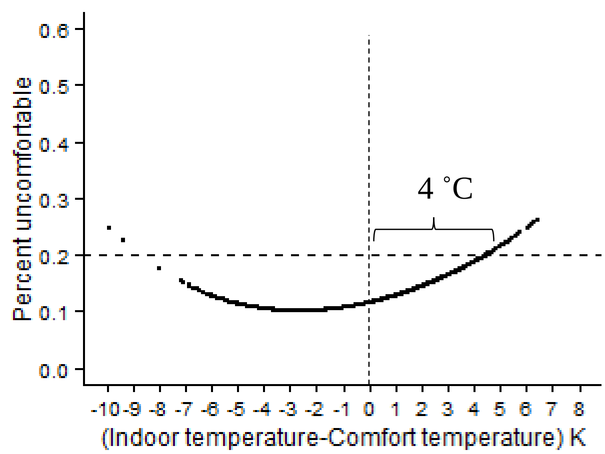

Figure 95. Percent uncomfortable with variation of indoor temperature from comfort temperature in Jaipur.

Location Dissatisfaction	**Variable**	**Coefficient**	**Std. error**	**p value**	**Nagelkerke's R^2**
Alameda warm unacceptable	ASC	-5.49	0.44	<0.001	0.04
	T_{in} - T_{comf}	0.32	0.16	<0.01	
Alameda cold unacceptable	ASC	-4.88	0.34	<0.001	0.13
	T_{in} - T_{comf}	-0.64	0.13	<0.001	
Jaipur warm uncomfortable	ASC	-2.24	0.08	<0.001	0.03
	T_{in} - T_{comf}	0.18	0.04	<0.001	
Jaipur cold uncomfortable	ASC	-3.9	0.18	<0.01	0.05
	T_{in} - T_{comf}	-0.27	0.06	<0.01	

Table 20. Coefficients of warm and cold dissatisfied logit with difference between indoor temperature and comfort temperature.

Thresholds of indoor temperature for 80% satisfaction

In naturally ventilated buildings, the range of indoor temperature is generally wider than in AC buildings. The range of indoor operative temperature for 80% satisfaction in NV and MM buildings from the RP-884 database is 19 – 27 ˚C during winter and 22 – 30 ˚C during summer (Zhang 2011). Two logits are fitted for Alameda and Jaipur in Figures 94 and 95 (similar to Figure 94 and Figure 95 but with indoor operative temperature as the explanatory variable). Warm and cold unacceptable/uncomfortable votes are flagged in the same way as in logits of these previous groups. Table 21 shows the coefficient summary of the logit models.

The indoor comfort temperature thresholds for 80% satisfaction in Alameda is 16 - 28 ˚C while in Jaipur it is 16 – 33 ˚C (Figure 96 and Figure 97). The dissatisfaction probability in Alameda was always less than 0.2 probably because of the mild climate. In Jaipur, the percentage of people uncomfortable increased sharply above 33 ˚C (Figure 97).

Location-Dissatisfaction	**Variable**	**Coefficient**	**Std. error**	**p value**	**Nagelkerke's R^2**
Alameda warm dissatisfied	ASC	-21.4	6.19	<0.001	0.13
	Tin	0.65	0.24	<0.01	
Alameda cold dissatisfied	ASC	7.58	1.95	<0.001	0.21
	Tin	-0.56	0.1	<0.001	
Jaipur warm dissatisfied	ASC	-9.62	0.55	<0.001	0.37
	Tin	0.30	0.02	<0.001	
Jaipur cold dissatisfied	ASC	2.8	0.91	<0.01	0.2
	Tin	-0.27	0.04	<0.001	

Table 21. Coefficients of warm and cold dissatisfied logits with indoor temperature.

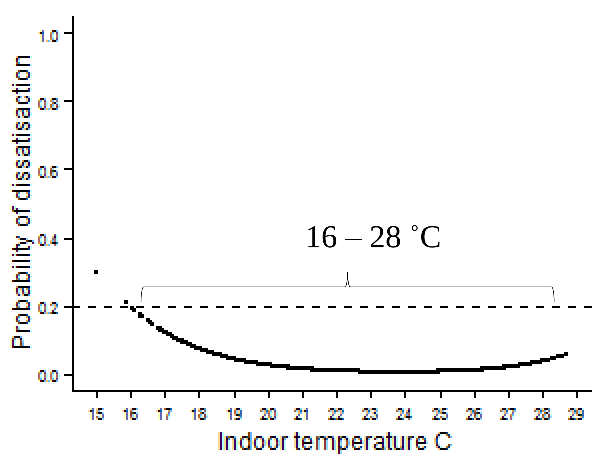

Figure 96. Probability of dissatisfaction with indoor temperature in Alameda.

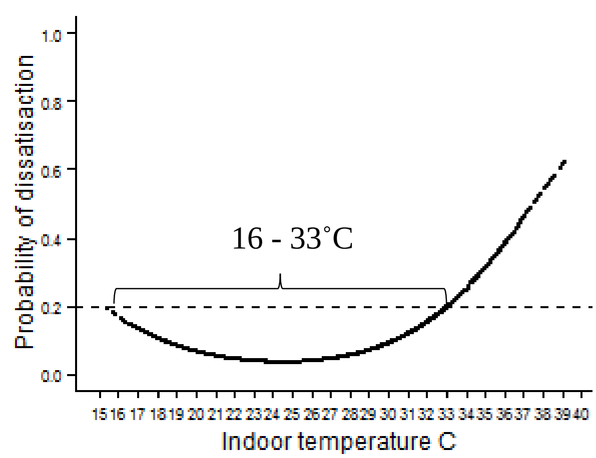

Figure 97. Probability of dissatisfaction with indoor temperature in Jaipur.

5.4. Discussion

Overall, thermal sensation lay mainly between 'slightly cool' to 'slightly warm', and a majority of the occupants found the temperature to be acceptable/comfortable in Alameda and Jaipur. Although, this is not surprising for Alameda as it is a mild climate, the results are quite striking for the semi-arid Jaipur climate. Interestingly, occupants from Jaipur voted that they felt cooler than those in Alameda in the moderate range of overlapping indoor temperature bins; 17 – 20 ˚C, 20 – 23 ˚C and 26 – 29 ˚C. This could be mainly because Jaipur buildings had higher air movement than the Alameda building due to a greater percentage of fan use. Another possible reason is that since Jaipur is predominantly a warm climate, occupants have physiologically or psychologically adapted to the warm conditions and thus felt the moderate temperature to be comparatively cooler. Thus there exists an interrelationship between building performance (indoor temperature and air movement), physiological adaptation and thermal sensation.

Investigating this interrelationship further, Figure 89 shows that in Alameda, almost all occupants found the indoor temperature acceptable even when they voted their thermal sensation away from 'neutral', i.e. either 'slightly cool' or 'slightly warm'. This is expected because the indoor temperature did not go very high and reached a maximum of 28 ˚C. In Jaipur, occupants voted to be comfortable when the thermal sensation was between 'slightly cool' to 'slightly warm' provided the indoor temperature was below 35 ˚C (Figure 90). In this figure, the indoor temperature range between 29 – 35 ˚C is particularly interesting because even in these warm conditions, occupants mostly voted in the three central categories of the thermal sensation scale and were comfortable. This implies that more passive strategies can be explored in warm climates to bring the indoor temperatures within this range if not below.

The differences in the neutral temperatures calculated for Alameda and Jaipur also illustrate the influence of outdoor weather on an occupant's thermal comfort opinion. The neutral temperature in Alameda during summer was 22.9 ˚C while in Jaipur it was 28.8 ˚C; a sharp 6 K rise. The corresponding average running mean temperature during summer in Alameda was 17.3 ˚C and 29.8 ˚C in Jaipur. The possible explanations for the occupant's acceptance of warmer temperature in Jaipur can once again be traced back to the IEQ in chapter 3 and adaptive actions in chapter 4. The mean indoor temperature in Alameda during summer was 25 ˚C while in Jaipur it was 30 ˚C. In both the climates, occupants used windows and fans which provided elevated air movement during warm conditions. The indoor air speed monitored in the Jaipur buildings was above 0.5 m/s in warm conditions. Moreover, occupants dressed more lightly in warm conditions in Jaipur; mean clo value during summer in Alameda was 0.55 while in Jaipur it was 0.45.

This finding is of relevance to both existing and new buildings. It calls for taking into consideration the underlying adaptations and the occupants' acceptance of warmer temperature at every design phase. The existing buildings, mainly those which rely solely on AC for providing comfort would benefit greatly in terms of energy savings by retrofitting with strategies for elevated air movement whereas the new buildings, if designed keeping occupants at the core of their design, would reap energy savings as well as better occupant satisfaction.

Comparison of the Alameda data with the ASHRAE standard 55 adaptive chart showed that the chart does a good job of predicting comfort within the 80% line in both the climates. However, two discrepancies were observed. In Alameda, there are many votes below running mean temperature of 10 ˚C, which is the region where the adaptive standard does not apply. In Jaipur, there are many comfortable observations that lie outside the 80% satisfaction line. Thus, in the ASHRAE adaptive model, there is a need to update the database with studies from cold climates and hot climates while possibly allowing the flexibility to define threshold comfort temperature per city/climate. Doing this will take into account the local and cultural factors that influence occupants comfort opinion.

Chapter 6: Thinking about the future- Mixed mode buildings

6.1. Introduction

MM buildings have a great potential for energy efficient design when the major responsibility of maintaining appropriate space temperature is borne by passive design elements, and air-conditioners are used only to meet programmatic requirements such as computer lab/conference room, or weather conditions with overly warm temperatures (Loftness 2007, Center for the Built Environment mixed-mode website). MM buildings also perform well as compared to purely NV and purely AC buildings in thermal comfort and air quality (Brager and Baker 2009).

Although MM buildings are becoming more common, there are not many studies that have evaluated comfort and adaptation in these buildings. Studies that have led to the adaptive comfort standards show clear evidence that occupants in NV buildings are comfortable over a broader temperature range than in AC (Brager and de Dear 1998, Nicol and Humphreys 2002) the unresolved question is whether the adaptive theory can be extended to MM buildings. In a zoned MM building, occupants in the NV zone frequently shuttle to the AC zone during the day and are aware of the environmental conditions in the AC zone. As a result, they might have different comfort expectations than occupants in purely NV buildings. Contrary to this point, access to adaptive opportunities like operable windows and fans might outplay the expectancy factor. In a zoned type MM building studied in Sydney Australia, occupants in the NV zone adapted using passive means and accepted a wider indoor temperature compared to the AC zone (Rowe 2004). Testing the hypothesis of expectation in a switchover type MM building, Deuble and de Dear found that status of the air-conditioner influenced occupant's thermal response. When the physical conditions were associated with a PMV value of +1, the actual occupant votes revealed a warmer thermal response in AC mode as compared to NV mode (Deuble and de Dear 2012).

Understanding thermal expectation, comfort response and physical environmental conditions in a MM building is crucial for a developing country like India where it is estimated that two-thirds of the commercial area needed by 2030 is yet to be built (Singh 2013). Room air-conditioner sales are fast growing and have doubled from 400,000 units in 2006 to 800,000 units in 2011, accounting for the highest energy consumption in the energy sector. The estimated installed inventory of AC's by 2016 is 10.2 million, which, needless to say, would mount unrealistic pressure on power plants (Natural resources defense council (NRDC) 2013, Phadke, World Bank report 2008).

The MM buildings from Jaipur analyzed in this thesis were zoned type where part of the building is NV and part of it is AC. These two zones will from now on be referred as 'AC zone' and 'NV zone' respectively. Designers have a choice for the buildings that are yet to be built: seal them completely and install air-conditioners or adopt a more sustainable approach of designing them as zoned type MM, selectively air-conditioning spaces only when and where needed, and design the rest of it to be naturally ventilated by deploying rigorous passive design strategies. To be able to opt for the latter, the environmental conditions and the corresponding influence of expectancy on the occupants in the NV zones of a zoned type MM building needs to be characterized.

6.2. Results

6.2.1. Temperature/ humidity distribution

Indoor operative temperature in the AC zone floated between 23 – 29˚C while the NV zone indoor temperature was warmer, and ranged between 29 – 36˚C (considering only those bins with more than 20 observation). Humidity level was also affected by the presence of AC, as would be expected. Humidity was maintained below 50% RH in 91% of the ‘AC zone’ observations, while the humidity shot above 50% RH in 50% of the NV zone observations (Figure 99). This significant difference in temperature and humidity is particularly important because these two variables are of great concern while designing MM buildings in a semi-arid climate. Other studies conducted in semi-arid have found that occupants are accepting of higher indoor temperature and humidity in NV buildings (Busch 1992, Indraganti 2010, Mallick 1996, Nicol 2004). We test this hypothesis here for the unique situation in a MM building where the occupants in the NV zone are well aware of the lower temperature and humidity in the AC zone.
Figure 100 shows the indoor – outdoor temperature occurrences in both the zones. The dotted line is where the indoor temperature equals outdoor. Interestingly, the indoors stayed cooler than outdoors for 80% of the observations in the NV zone. This was mainly because the NV zones were shielded from direct solar radiation (by balconies and corridors) in most of the buildings and the construction material had high thermal mass. These buildings were constructed with conventional building practices such as double height ceiling, low window to wall ratio (20 – 30%), thick stone walls with plaster on both sides (330 mm) and also brick construction (double brick type - 229 mm) with plaster.

Overlaying the observations on the psychrometric chart (Figure 101) shows that 58% of the observations from the AC zone were inside the comfort zone defined by ASHRAE standard 55. When the physical observations were inside the comfort zone, in 99% of these occurrences the occupants voted that they were comfortable. However, even when the physical observations were outside the comfort zone, there was still a high number, 93%, who were comfortable. The NV observations were clearly outside the comfort zone. In these NV zone observations, occupants voted to be comfortable 80% of the time when indoor temperature was less than 33 ˚C.

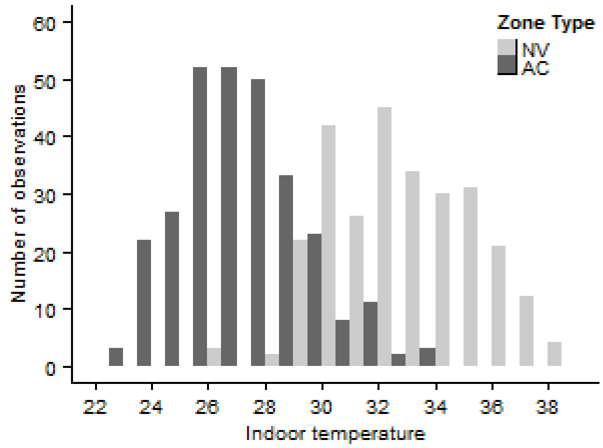

Figure 98. Indoor temperature distribution in NV/AC zone.

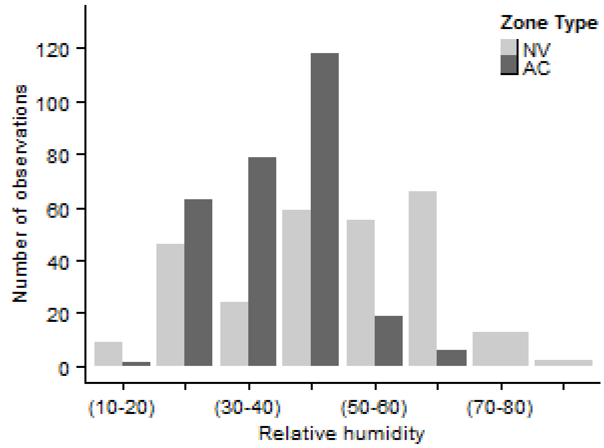

Figure 99. Humidity distribution in AC/NV zone.

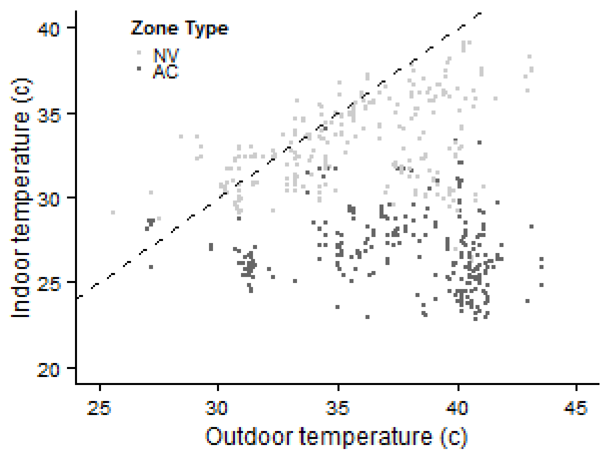

Figure 100. Indoor/outdoor temperature distribution in NV/AC zone.

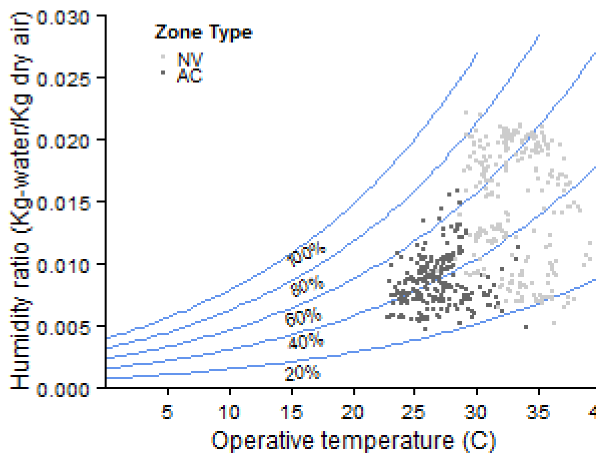

Figure 101. Observations overlaid on the psychrometric chart.

6.2.2. Humidity sensation and air movement in NV zone

Although, Jaipur has a dry climate, 50% of the observations in the NV zone were found to have relative humidity above 50%. Figure 102 shows the humidity sensation of occupants in the NV zone for different relative humidity bins. Although humidity sensation is above neutral for relative humidity above 50%, the median lies at “Slightly humid” and there were negligible votes at “Very humid”. The forgiving humidity sensation could be because of air movement, which is shown in Figure 102 for different temperature bins, for both the NV and AC zones. Air movement is seen to be significantly higher ($p<0.05$) in the NV zone compared to the AC zone in two of the four temperature bins with overlapping observations (represented by a solid dot just above the x axis). The horizontal dotted line shows the ASHRAE recommended limit for draft 1.2 m/s (ANSI/ASHRAE 2010b). Based on these physical measurements, 24% of the observations in the ‘NV zone’ were found to have air speed more than 1.2 m/s while it was only 3% in the ‘AC zone’. In the NV zone, mean air speed for indoor temperatures above 25˚C was 0.9 m/s, which is higher than the mean air speed found for Pakistani subjects (0.45 m/s) in NV buildings in the same indoor temperature range (Nicol 1999).

Investigating the indoor air speed with humidity, Figure 103 shows the range of air speed for different relative humidity bins. We do the analysis just for the NV zones since humidity above 50% was rarely observed in the AC zones (Figure 99). Air speed at humidity above 50% in the NV zone is quite high around 1 m/s (Figure 103). The high air velocity in the NV zone hints at occupant's tendency to use windows and fans to keep themselves comfortable at higher temperature and humidity, as observed in other field studies carried out in NV buildings in hot climates (Cândido 2010, de Dear 1991, de Dear and Fountain 1994, Mallick 1996, Sharma and Ali 1986)

The mixed mode configuration brings forth another perspective to the findings: can comfort be provided in the NV zone by ensuring adequate opportunities to adjust air movement in the space, even when occupants are intermittently exposed to conditions of the AC zone where comfort is achieved predominantly be temperature control?

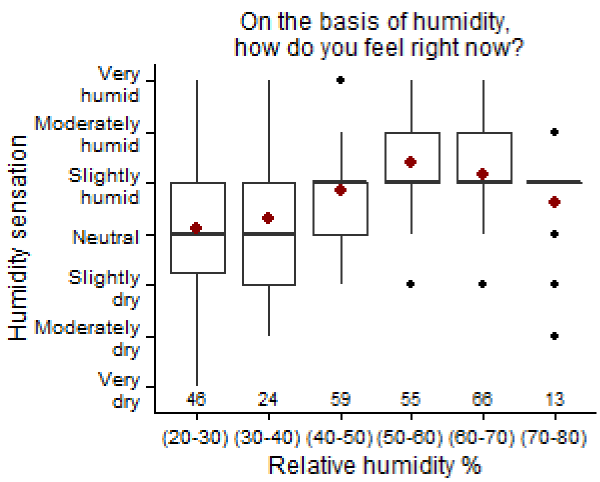

Figure 102. Humidity sensation binned by relative humidity in NV zone.

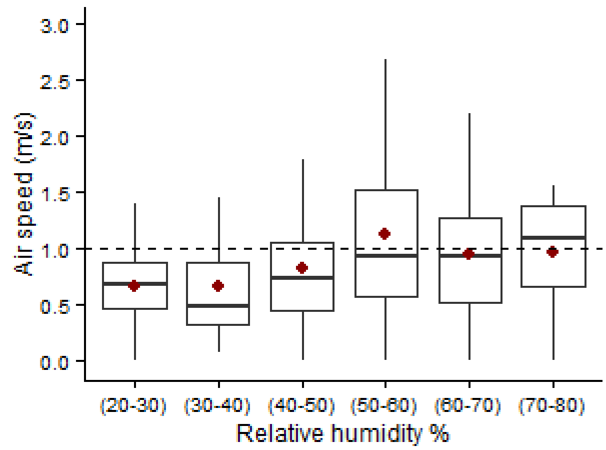

Figure 103. Air velocity binned by relative humidity in NV zone.

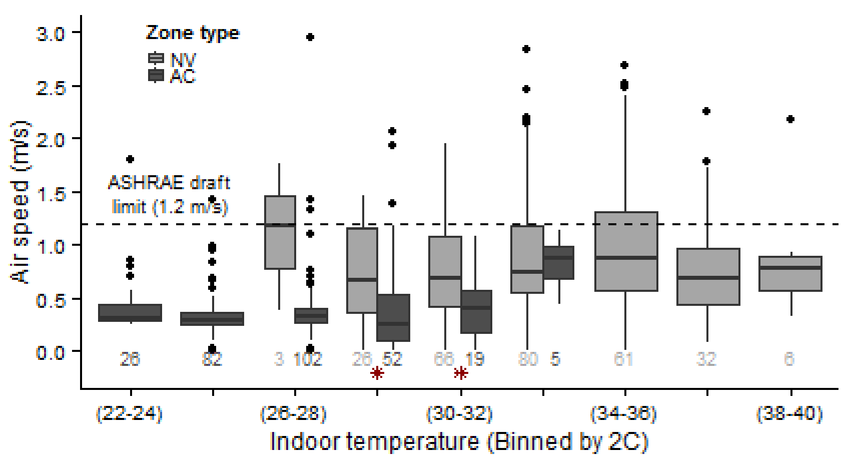

Figure 104. Air speeds in NV/AC zone binned by indoor temperature.

6.2.3. CO_2 concentration

A significant relationship between sick building syndrome and CO_2 concentration has been observed at a threshold of 800 ppm (Apte 2000). Results from CO_2 monitoring show that concentrations in the NV zone are much better than in the AC zone. 88% of the observations in the NV zone have a CO_2 concentration less than 800 ppm as compared to only 51% in the AC zone (Figure 105). Surprisingly, 50% of the observations in the AC zone recorded CO_2 concentration of above 2400 ppm. This could be because windows were never opened in the AC zones and they did not have any provision for mixing fresh air especially in offices with high occupancy. As noted earlier in the IEQ section, the average office floor area per occupant in government offices the US is 20 m^2, while it is only 5-10 m^2 in Indian offices (Singh et.al. 2013). A significant influence on occupant's decision making has been observed when the indoor CO2 level is higher than 1000 ppm (Satish 2012). The high CO_2 concentrations can also cause discomfort due to bio effluents (ANSI/ASHRAE 2010a, Persily 1997).

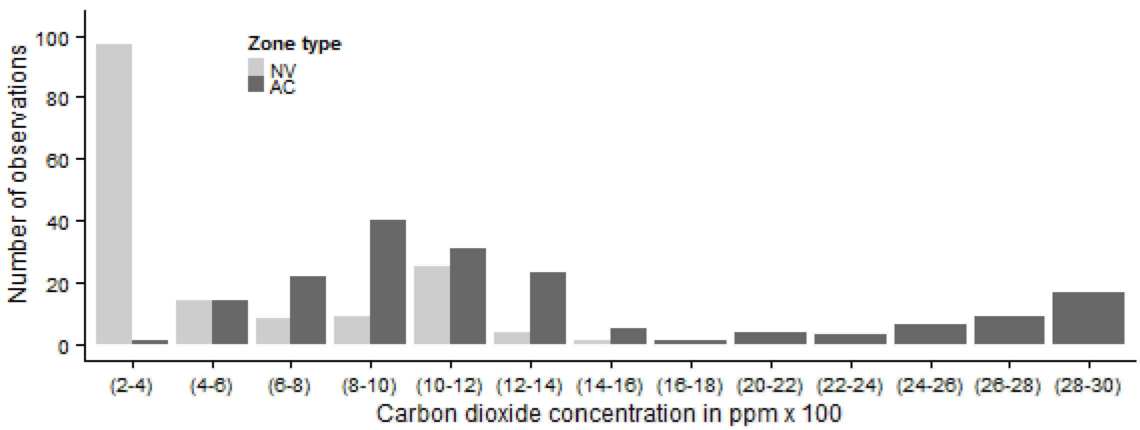

Figure 105. CO_2 concentration in NV/AC zone of MM building.

6.2.4. Use of adaptive control in NV zone

Thermal comfort is directly influenced by behavioral adaptation in addition to psychological and physiological adaptation (Brager and de Dear 1998). By extending the opportunities for behavioral adaptation in mixed mode buildings compared to conventional sealed buildings, the question becomes whether occupants in the NV zone of a MM building use these adaptive actions to the same degree as in purely NV buildings. European and Pakistani mixed mode buildings have been found to follow similar control patterns of window opening and fan operation as in purely NV buildings (Rijal 2008). In this paper, we do a descriptive analysis of window, fan, blind and balcony door use in the NV zone per degree indoor temperature to evaluate the proportion of usage in each bin. We chose indoor over outdoor temperature as the metric for binning because it captures the information at the individual building level, which might vary from building to building for the same outdoor temperature, as noted by Robinson (Robinson 2006).

Windows

Windows in the AC zone were closed in all the observations while those in the NV zone were sparingly opened; only 38% open overall (Figure 106). The bar graph does not show any clear trend and it seems like fewer windows are opened at indoor temperatures above 37˚C. This might be because outdoor temperature is warmer than indoors in 80% of the observations (Figure 100).The benefit of purging the warm indoor air and the disadvantage of bringing in even warmer outdoor air seem to be acting against each other.

Fans

Fans were found to be on in 98 % of the observations in the NV zone. This result is contrary to other studies that found windows to be the most widely used control option (Haldi and Robinson 2008; Liu 2012). However, the high percentage of fan use reveals that occupants like to have air movement. It also partially explains the window opening behavior; when the outdoor temperatures are higher than indoors, occupants prefer to keep their window closed and turn on the fans to provide air movement, which is an appropriate strategy.

Blinds/curtains

Adjusting blinds is an important adaptation strategy in hot climates since direct sunlight or glare is thermally and visually unpleasant at high indoor temperatures. Overall, 68% of the blinds were found to be open in the NV zone (Figure 108). Fewer blinds were found open as the indoor temperature increased above 33˚C, possibly to avoid heat gain and glare.

Balcony doors

Overall, 72% balcony doors were open. Balconies can be an integral part of climate responsive building design in hot climates as they act as thermal buffer zones, reducing the direct solar exposure to the interiors while providing air movement. In most of our buildings, balconies were located on the side of the façade that received direct sunlight; towards South and South-west.

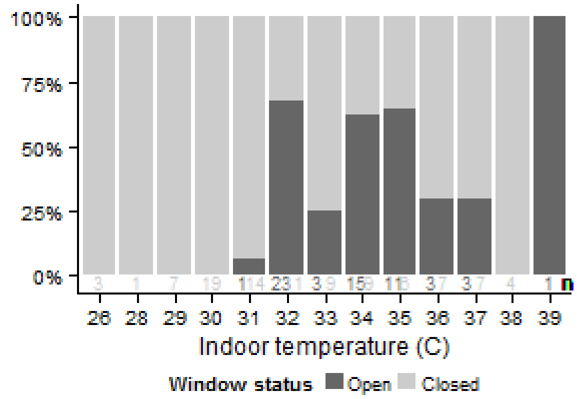

Figure 106. Percentage of windows open/closed in the NV zone of MM.

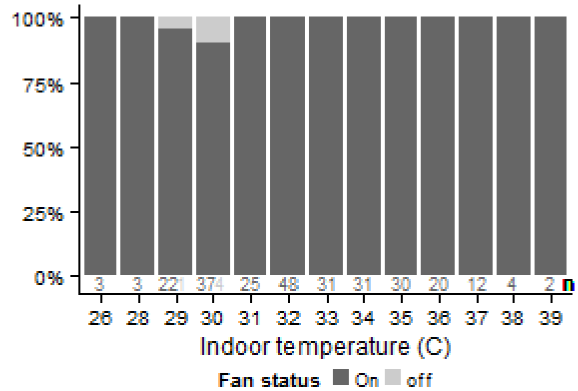

Figure 107. Percentage of fans on/off in the NV zone of MM.

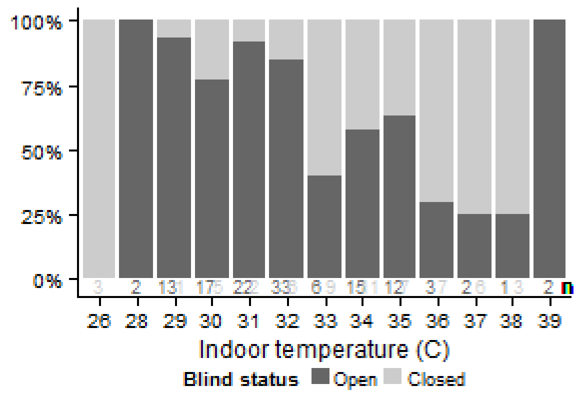

Figure 108. Percentage of blinds open/closed in the NV zone of MM.

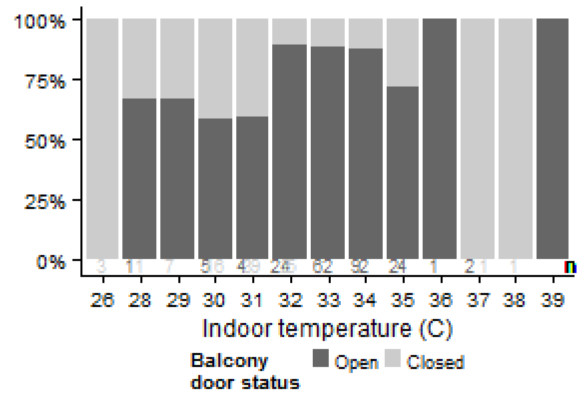

Figure 109. Percentage of balcony doors open/closed in the NV zone of MM.

6.2.5. Comparison with purely NV buildings

In the 17 purely naturally ventilated buildings surveyed and monitored in this study, a similar degree of adaptive control usage was observed for windows and fans. Overall, windows were open in 33% and fans were turned on in 81% of the observations. Interestingly, all of the 42 observations at indoor temperature above 36 ˚C had windows open. Blinds were open in 58% while balcony doors were open in 83% of the observations.

6.2.6. Thermal comfort

Thermal sensation in AC and NV zone

Overall, occupants in 70% and 87% of the observations in NV and AC zones, respectively, voted within the thermal sensation limit of ±1 (slightly cool – slightly warm). Figure 110 shows the box plot of thermal sensation votes in both the zones for bins of indoor temperature. When the indoor temperatures were between 30˚C – 38˚C in the NV zone, the median value of thermal sensation was "slightly warm". This indicates that occupants in the NV zone do not feel overly warm at higher indoor temperatures and adapt themselves to the indoor conditions using controls such as operable windows, fans, blinds and balcony door. This is particularly interesting because of the expectancy factor discussed earlier, where there was concern that NV occupants' visits to the AC zones would lead to their desire for cooler temperatures. Our results show that adaptation to the warmer temperatures in the NV zone overrides the influence of the AC zone experiences on thermal expectations.

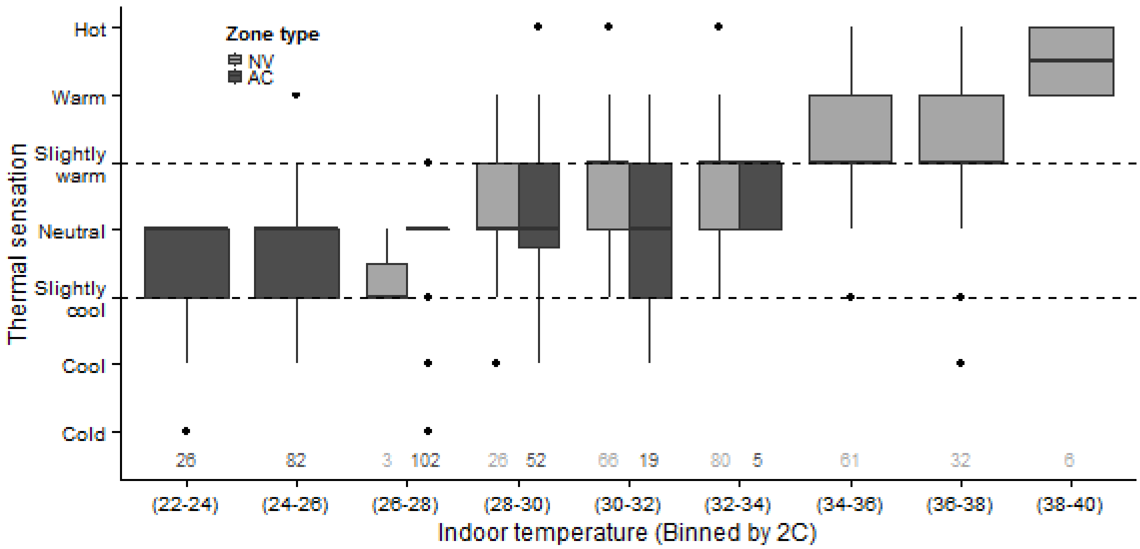

Figure 110. Thermal sensation vs. indoor temperature.

Relation between thermal sensation and comfort

The most appropriate metric for thermal comfort has often been debated because of its inherent subjective definition. The ASHRAE Standard 55 adaptive model uses thermal sensation as the metric to calculate the percentage of people satisfied. However, thermal sensation doesn't necessarily reflect an occupant's comfort opinion. An occupant might vote that to feel warm, but may still be comfortable. This might be due to the three adaptations pointed out in the adaptive comfort theory- behavioral, physiological and psychological, or because of the pleasant experience in transient temperature conditions (Brager and de Dear 1998; Kuno 1995).

In our survey, occupants recorded their comfort opinion on a 5-point scale (0=Very uncomfortable 5=Very comfortable). Figure 111 (NV) and Figure 112 (AC) shows the percentage of occupants comfortable, binned per degree indoor temperature and thermal sensation. Only those bins with five or more observations are shown. Interestingly, the range of thermal sensation is much broader in the NV zone on the warmer side while it is broader on the cooler side in the AC zone. In the NV zone, when the indoor temperature was between 30-35˚C, occupants voted to be "neutral" or "slightly warm" in 73% of the observations (123 out of 169). Out of these 123 observations, 84% were comfortable (Figure 111). Occupants in the AC zone voted to be comfortable in 96% of the observations (Figure 112). However, there are some slightly cool and cool votes that occur at indoor temperature of 24 -27˚C, which shows that these AC zones run a potential risk of overcooling the building. The comparison of thermal sensation and comfort between NV and AC zones illustrates that in a semi-arid climate, air-conditioners do a good job in providing comfort, but it is also possible to keep occupants comfortable without having to use an air-conditioner.

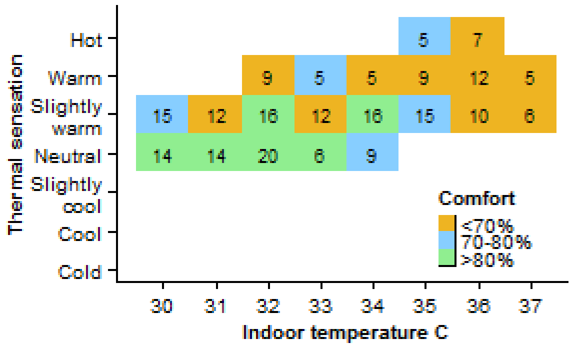

Figure 111. NV zones: percent comfortable based on indoor temperature and thermal sensation.

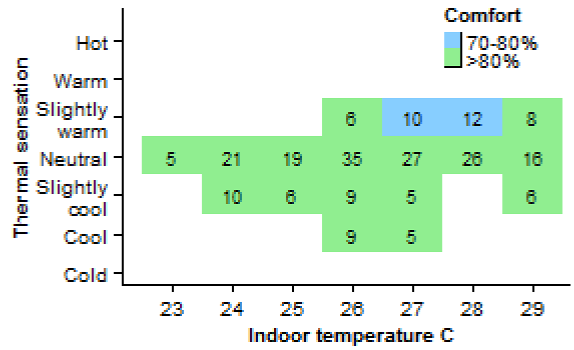

Figure 112. AC zones: percent comfortable based on indoor temperature and thermal sensation in AC zones.

Comfort temperature range in NV and AC zone

In the NV zone, more than 70% of occupants voted to be comfortable in indoor temperatures ranging from 29˚C – 34˚C, while in the AC zone the range was 23˚C – 29˚C (considering only those bins with more than 20 votes). The higher comfort temperature range in the NV zone clearly supports the adaptive theory, which posits the acceptance of a wider range of comfort temperature. The upper limit of the observed comfort range in the AC zone is also higher than the one defined in ASHRAE Standard (Figure 101), which basically means occupants in the AC zones of these buildings also adapted to warmer than neutral indoor temperatures.

When viewed from the perspective of a mixed mode building, the comfort range presents an interesting scenario. Two groups of people in the same building are exposed to a relatively low and high temperature range (AC and NV zone). The ones in the lower temperature range are comfortable; but the majority of those in the higher temperature range, barring a few observations when the indoor temperature is greater than 36 ˚C, are also comfortable. This is a promising result for new constructions in hot climates, which can rely more on passive design to provide comfort cost efficiently.

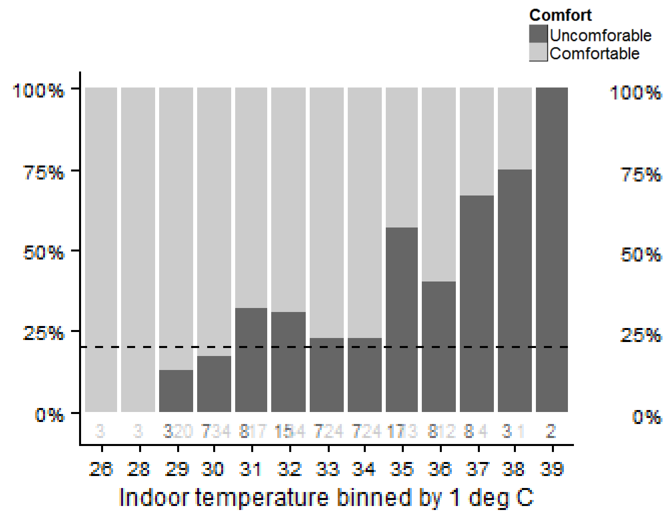

Figure 113. Percentage people dissatisfied in NV zone binned by indoor temperature.

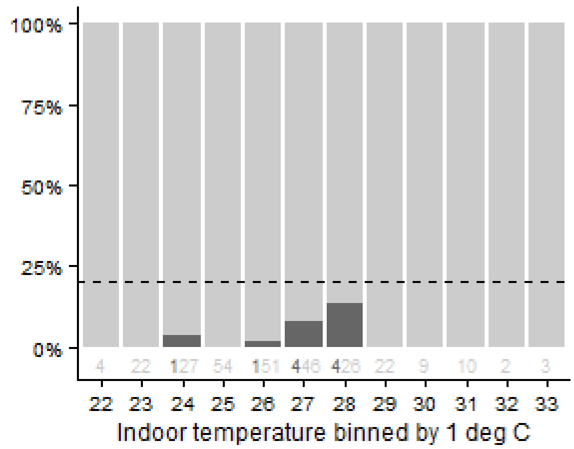

Figure 114. Percentage people dissatisfied in AC zone binned by indoor temperature.

Comparison of NV zone temperature with ASHRAE Standard 55, EN 15251 and an adaptive chart developed for hot-humid Indian climate

ASHRAE adaptive standard 55 gives a relation between running mean temperature and comfort temperature in an unconditioned building, but does not provide any guidelines for modeling comfort in a mixed mode building. However, it allows the comfort model to be applied in spaces that do not have a mechanical cooling system installed (2013). EN 15251, on the other hand, gives a similar relationship between comfort and running mean temperature while extending the applicability of the standard to spaces that have mechanical conditioning installed but not in operation (Nicol and Humphreys 2002). Technically, both the adaptive models can be applied to the NV zone of a mixed mode building.

To verify this hypothesis of applicability of the adaptive models in the NV zone, we compare the percentage of people comfortable in our study with the ASHRAE Standard 55, EN 15251 and an adaptive model developed for hot-humid climate of South India (Indraganti 2014) (Figure 115, Figure 116 and Figure 117).

Only 53% (145 out of 274) of the observations in the NV zone were in the temperature range where ASHRAE adaptive chart is applicable (i.e., running mean outdoor temperature less than 33˚C) (Figure 115). Of the 274 total NV zone observations, only 20 were inside the 80% satisfaction zone (outermost lines) defined by the adaptive chart (Figure 115), and 85% of these 20 occupants voted that they were comfortable. But there was still a very high level of comfort above the adaptive comfort zone limits. In the area above the 80% satisfied limit, but below the running mean 33˚C limit of applicability (shown in a dotted blue line), 75% of the occupants were comfortable. When the running mean was greater than 33 ˚C, occupants voted comfortable in 60% of the 129 observations.

Comparing with EN 15251 standard (Figure 116), only 57 of the 274 observations fell in the temperature zone where the adaptive chart is valid (running mean temperature less than 30 ˚C).

This is probably because EN 15251 was developed from field study data from European countries, which did not have hot summers like Jaipur (Nicol and Humphreys 2002). We do not further evaluate with respect to EN15251 due to the limited number of valid votes.

For the adaptive chart developed from a field study in hot-humid climate of South India (Indraganti 2014), 53% of the observations from the NV zone were within the temperature range where the chart was valid (running mean temperature less than 33 ^{o}C) (Figure 117). Considering ± 4K deviation from neutral temperature as the comfort threshold, 81% occupants voted to be comfortable inside the comfort zone. Out of the 56 observations that were outside the comfort range, 70% were comfortable.

These results indicate two things, based on the conditions in this study:

- The comfort responses in NV zone of mixed mode can be modeled similarly to a purely naturally ventilated building, while noting that in this particular study we found high degrees of comfort at temperatures even high than the recommended upper limits
- Amongst the three adaptive charts compared above, ASHRAE Standard 55 and the adaptive model developed by Madhavi et.al. represent comfort in this hot climate better than EN15251.

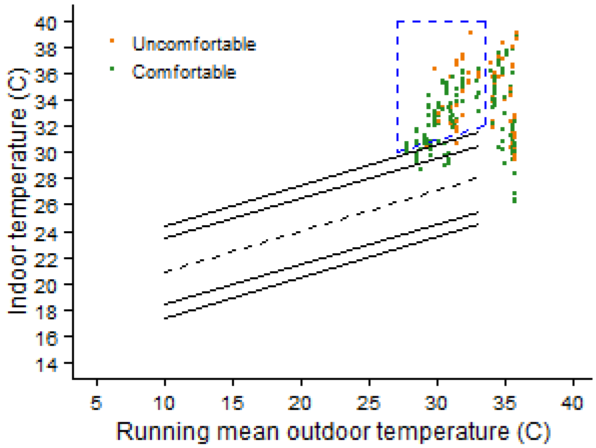

Figure 115. Comfort votes from NV zone overlaid on the ASHRAE Std 55 adaptive chart.

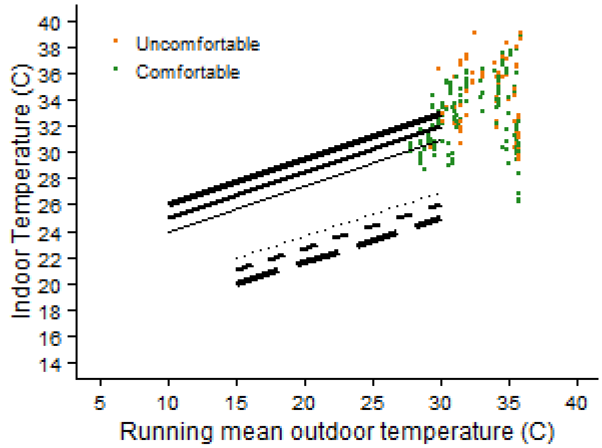

Figure 116. Comfort votes from NV zone overlaid on EN 15251 adaptive chart.

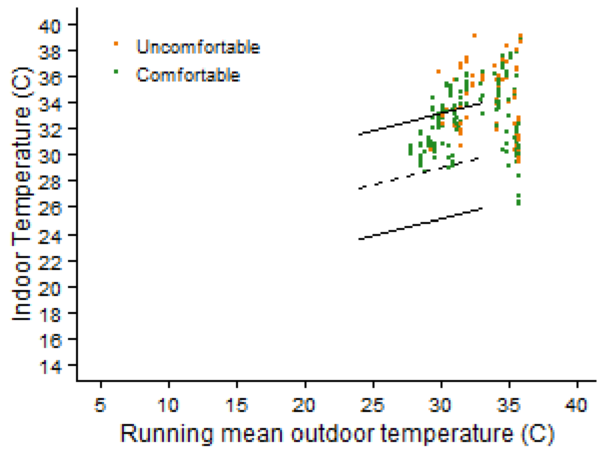

Figure 117. Comfort votes from NV zone overlaid on adaptive chart developed by Madhavi et.al. for South Indian climate.

6.3. Discussion

Physical measurements and thermal comfort survey responses from this study shows that a zoned-type mixed mode building has the potential to save energy and also provide comfort.

Indoor temperatures in the NV zones were found to be on an average 2 - 5 ˚C lower than outdoor temperature even when the outdoor temperature was above 35˚C (Figure 100). In addition to revealing that the building envelope is performing well in a semi-arid climate, this result raises an interesting question: Is the comfort opinion of a space driven by the difference in indoor and outdoor temperature, as opposed to the absolute value of either one of them? In other words, if it is very hot outside a temperature drop of few degrees indoors could be sufficient to keep occupants comfortable.

High air speeds at higher relative humidity and temperature, apparently due in part to the frequent turning on of fans in the NV zone, shows that occupants prefer to have air movement. In addition to this, 70 - 80% comfort at a high indoor temperature range of 29 – 34 ˚C is evidence of thermal adaptation where occupants are comfortable beyond the neutrality defined by the uniform conditioning-based PMV method. Occupants' ability to adapt to the high humidity and temperature in the NV zone by accessing windows, fans, blinds and doors seem to override any potential expectations of having conditions similar to AC zone. This implies that a building can be selectively air conditioned based on programmatic requirement or zone location (perimeter and core), while the other areas can be designed as a naturally ventilated building, and one still gets the benefits of adaptive comfort.

The higher temperature range for comfort in the NV zone also gives designers an opportunity to explore various passive design strategies in hot-dry climates that reduce indoor temperatures, which might not be far enough to meet the neutral temperature defined by the PMV based method. Studies evaluating the performance of passive design in hot-dry Indian climates, such as using passive downdraft cooling towers, have reported energy savings as high as 64% compared to air conditioned building (Ford 1998), and a temperature reduction in the range of 12 ˚C – 14 ˚C. Other passive strategies that have been found to be effective are mud walls, thermal insulation over roof and nocturnal cooling (Chel and Tiwari 2009; Ford 1998; Nahar 2003).

Although experiences in the AC zones did not seem to influence thermal expectations of occupants of the NV zone in our study, these results cannot necessarily be extended to a switchover type mixed mode building. The unanswered question in a switch over type MM building is: would installing an air conditioner influence the adaptive actions that occupants would have otherwise exercised, such as opening a window or turning on a fan?

Designers encounter two main challenges in a switchover type MM building. For a system that switches between NV and AC automatically, there does not seem to be a standard for deciding the temperature at which the switch over would happen. If the decision to switch on and off the air conditioner is left to the occupants, there is no certainty that occupants would actually turn off the air conditioner when the outdoor weather is suitable to open windows. Mutual consensus between occupants to turn off the air conditioner would also be a challenge.

In light of these difficulties, zoned type mixed mode buildings have an advantage over switchover types. The energy saving in the unconditioned area is guaranteed and there are fewer concerns of HVAC control. Strategic location of programs within a building considering cooling requirements and appropriate use of passive design seems to be a promising way of reducing the cost of comfort in the 70% of the buildings that are yet to come up in India.

Chapter 7: Comfort and energy saving

The results from this study show that occupants are comfortable in a wider range of indoor temperature in NV buildings in both mild and hot climates. Even in zoned type MM buildings, occupants are comfortable over a wider range of indoor temperature despite having intermittent exposure to air conditioned environments. In NV buildings, since there are no active cooling systems, energy consumption is low and consists mainly of fan, equipment and lighting power consumption. On the other hand, AC/ MM buildings have the air conditioner power consumption in addition to equipment and lighting. In order to accrue the energy saving benefits, there is a need to apply the thermal comfort findings in the design process especially while deciding the programs in the building and HVAC system sizing. In other words, the question of when, where and how to use air conditioning needs to be evaluated in light of the field based thermal comfort results. The potential for energy saving by is greater in a hot climate compared to a mild climate. Therefore a typical office building from Jaipur is discussed in this section.

Figure 118 shows the comfort zone defined by the ASHRAE standard 55 adaptive chart and Figure 119 shows the comfort zone defined by the adaptive chart developed from purely NV building data. The modeling approach of the adaptive chart in Figure 119 was discussed in section 5.3.1; Figure 94 and Figure 95. On the warmer side, ASHRAE chart says the indoor temperature can drift to maximum of 4.5 ˚C above the neutral temperature for 80% satisfaction, considering the allowance for elevated air movement with local control (2010b). The comfort line for Jaipur on the other hand is steeper than ASHRAE and the indoor temperature can drift to a maximum of 4 ˚C above the comfort temperature for 80% satisfaction. Outside this region is when air conditioning is needed.

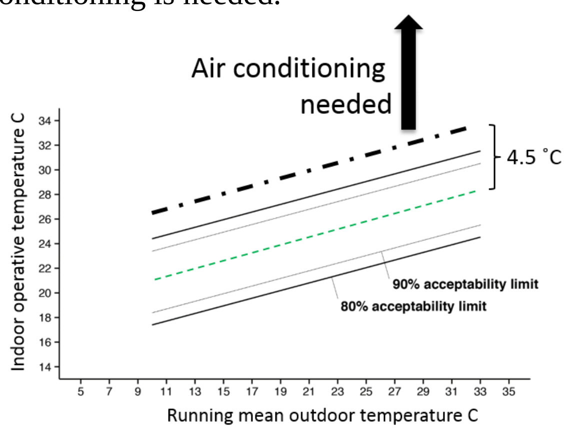

Figure 118. Comfort zone defined by ASHRAE std 55.

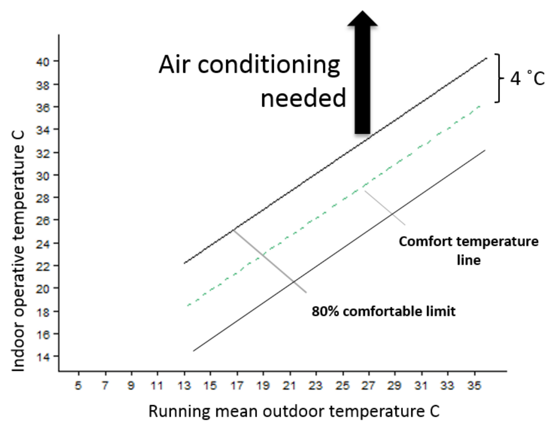

Figure 119. Comfort zone defined from Jaipur data.

A typical NV office building of three storey was simulated using Design builder™. Inputs of building envelope, shading, glazing and internal loads were chosen to be close to those observed in majority of the buildings. This included having glazing with single pane clear glass (40% window wall ration on the North wall, 10% on East, West and South wall), overhangs with 1 m depth and wall construction made of 200 mm brick construction sandwiched between 200 mm layer of cement plaster.

Figure 120 and Figure 121 shows the degrees above comfort calculated based on the ASHRAE and the Jaipur adaptive chart respectively. The x axis is the month, y axis is the hour of the day and intensity of color represents the degrees above comfort. In order to make it easier to identify only those hours when cooling is needed, the color scale is adjusted to start when the degrees above comfort is greater than that for 80% satisfaction; 2.5 ˚C for the ASHRAE based cooling hours (Figure 120) and 4 ˚C for the Jaipur data based cooling hours (Figure 121).

The cooling hours predicted by ASHRAE adaptive chart in Figure 120 shows that cooling is needed throughout the day from March to December while the cooling hours predicted by the Jaipur adaptive chart in Figure 121 shows that cooling is needed only during the afternoons.

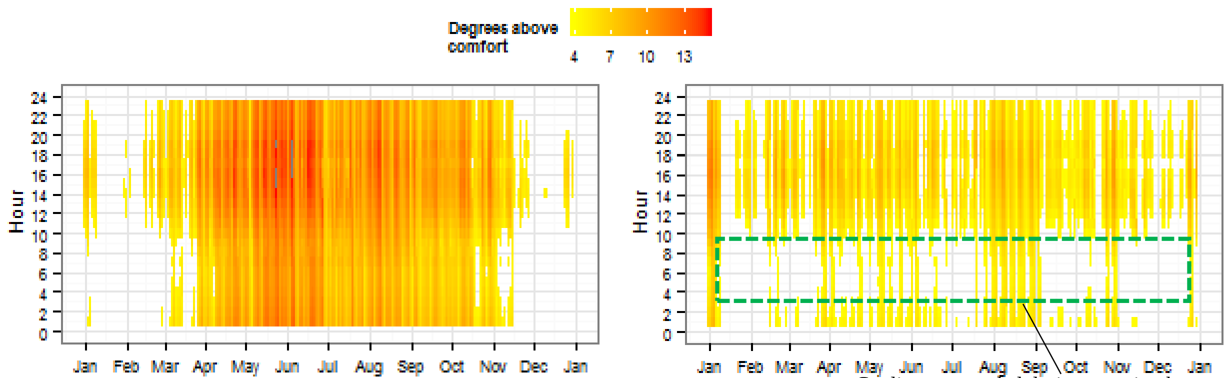

Figure 120. Time of year when cooling is needed based on ASHRAE std 55.

Figure 121. Time of year when cooling is needed based on Jaipur data.

Figure 122 (a) and (b) show the histogram of the difference between indoor and comfort temperature excluding weekends. The ASHRAE std 55 comfort chart, when accounting for the elevated air movement, predicts that cooling is needed in 64% of the occupied hour during the year while the Jaipur data predicts the cooling hours to be 56% of the occupied hours. There is no major difference in the percentage of cooling hours predicted by the two models.

Although these results are subject to the accuracy of the energy simulation model, it is worth mentioning that they open up opportunities to think about efficient ways of designing a mixed mode building. Workspaces in many offices are being designed to be collaborative and occupants have the flexibility of choosing their workstation. This allows occupants to choose a workspace based on the type of work they need to get done. For instance, when the work demands concentration, they can move to quieter areas and when they need to interact with their colleagues, they can do so in areas marked for such activities. This analogy can be extended to temperature and thermal comfort. During the course of the day, occupants can be given a choice to move around areas that are conditioned and those that are not depending on the type of work/ program. Air conditioned common lobbies could serve as recreational or relaxation areas mainly for a short period of time.

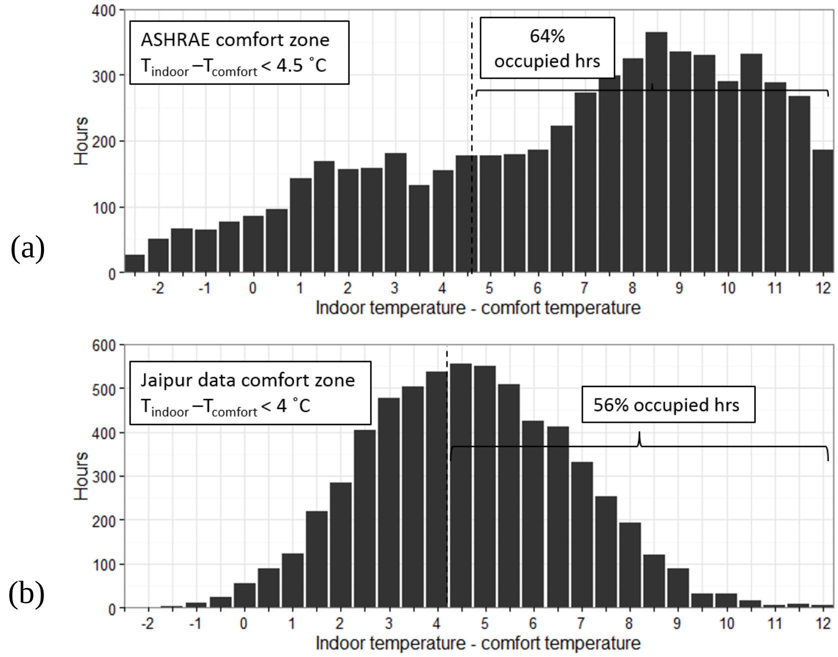

Figure 122. Cooling hours predicted by (a) ASHRAE adaptive std 55 (b) Jaipur data.

Chapter 8: Conclusion

Summary

Indoor environmental quality (IEQ), adaptive actions such as adjusting clothing, windows and fans, and thermal comfort was evaluated for a naturally ventilated (NV) building in Alameda based on the data collected by a yearlong monitoring and for 17 purely NV and 11 mixed-mode (MM) buildings in Jaipur based on the data collected by a three yearlong monitoring. Data from 6 purely Air conditioned (AC) buildings in Jaipur was evaluated for comparing CO_2 levels with purely NV buildings. In the 11 MM buildings, a comparison of IEQ, adaptive action and thermal comfort was done between the AC and the NV zone. New ways of data visualization were explored and statistical models were developed leading into the following analysis:

- A comparison of indoor temperature and relatively humidity (RH) between the NV building from Alameda and the buildings from Jaipur in light of climatic and cultural differences
- An evaluation of airspeeds and air velocity preferences in NV buildings in Jaipur by considering window and fan usage.
- An evaluation of CO2 levels in the NV building from Alameda and the AC and NV buildings from Jaipur. The analysis also included a comparison of the CO2 levels when windows were open and closed.
- A linear regression model to predict clothing in the Alameda and Jaipur buildings based on indoor and running mean outdoor temperature.
- A probabilistic model to predict window status in the Alameda building by taking into account idiosyncrasies of the explanatory variables. A unique feature of this model is that it includes parameters which are important but not generally modeled such as ‘time of day’, ’season’ and ‘inertia’.
- A probabilistic model to predict the number of windows open in the Alameda building.
- A probabilistic model to predict fan status in the Alameda building.
- A probabilistic model to predict window and fan status in NV buildings in Jaipur.
- A comparison between thermal sensation vote for different indoor/outdoor temperatures in NV buildings in Alameda and Jaipur.
- A linear regression model to predict thermal sensation during summer and winter in NV buildings in Alameda and Jaipur.
- An evaluation of thermal comfort metrics; sensation, comfort and acceptability. The analysis aimed to get a better insight at the relationship between these metrics.
- A model to predict percent dissatisfied in NV buildings in Alameda and Jaipur. This model partially overcomes the limitations of the ASHRAE std 55 such as averaging of thermal comfort votes per building and assuming limits of thermal sensation for 80% satisfaction.
- A comparison of indoor temperature, RH, air speed, CO2 concentration, adaptive actions and thermal comfort between the AC and NV zones of a zoned type MM building.
- An evaluation of times when cooling is needed in Jaipur based on simulation.

Key takeaways from Indoor environmental quality analysis:

- **Indoor temperature.** Indoor temperature in Alameda was significantly lower than Jaipur but occupants were satisfied with temperature in more than 85 % of the observations in both the climates.

- **Relative humidity.** RH was below 50 % in most of the observations in Alameda but it drifted in the range of 70 – 80 % in Jaipur. Occupants perceived humid conditions as slightly humid in the presence of air movement. Thus the challenge of humidity driven discomfort can be efficiently met by having elevated air movement.

- **Air speed.** High indoor air speeds were observed in the NV buildings in Jaipur and occupants preferred to have this elevated air movement. Ceiling fans provided most of the air movement compared to operable windows.

- **Carbon dioxide.** CO_2 levels in the NV buildings were well below the threshold of concern in Alameda and Jaipur. CO_2 levels were also significantly lower when the windows were open as compared to when they were closed. However, in Jaipur the mean CO_2 levels in the AC buildings were higher than the NV buildings almost by 1700 ppm.

Key takeaways from behavioral adaptation analysis:

- **Clothing adjustment.** Occupants in Jaipur dressed lighter than those in Alameda during summer and winter. Outdoor running mean temperature best explained clothing levels in Alameda while clothing level in Jaipur was best explained by indoor temperature. This could be mainly because the buildings in Jaipur tracked the outdoor temperature more closely than the Alameda building.

- **Window adjustment.** The window status models developed in this thesis allow for a more accurate prediction of window status as they take into account parameters beyond temperature such as time of day, season and inertia. Idiosyncrasies prevailed in the influence of explanatory variables on the window status in the Alameda building. Outdoor temperature, time of day, season and inertia were the significant variables that best explained the window status in the Alameda building while outdoor temperature, difference between outdoor and indoor temperature and time of day best explained window status in the Jaipur buildings.

- **Fan adjustment.** Fans were not used very often in the Alameda building compared to Jaipur. Outdoor temperature, time of day, season and inertia significantly explain the fan status in the Alameda building while the fan status in Jaipur is best explained by outdoor temperature, difference between indoor and outdoor temperature, time of day and season.

Key takeaways from thermal comfort analysis:

- **Thermal sensation.** Thermal sensation opinion in both the climates varied based on the outdoor climate. Occupants in the semi-arid climate of Jaipur had a higher summer neutral temperature compared to the occupants in the mild climate of Alameda.

- **Comfort temperature.** The comfort temperature for 80% satisfaction ranges were from 16 – 28 ˚C in Alameda and 16 – 33 ˚C in Jaipur. Both these ranges were much wider than the PMV defined comfort range.

Key takeaways from mixed-mode analysis:

- **Field based data.** Indoor temperature, RH and air velocities in the NV zone were higher than in the AC zones. Fans were turned on almost all the time and occupants were comfortable in the warmer temperatures of the NV zone.

- **Comfort model.** The ASHRAE Standard 55 adaptive model and the adaptive model developed by Madhavi et.al best modelled comfort in the NV zone of the MM buildings in a semi-arid climate compared to the EN15251 standard.

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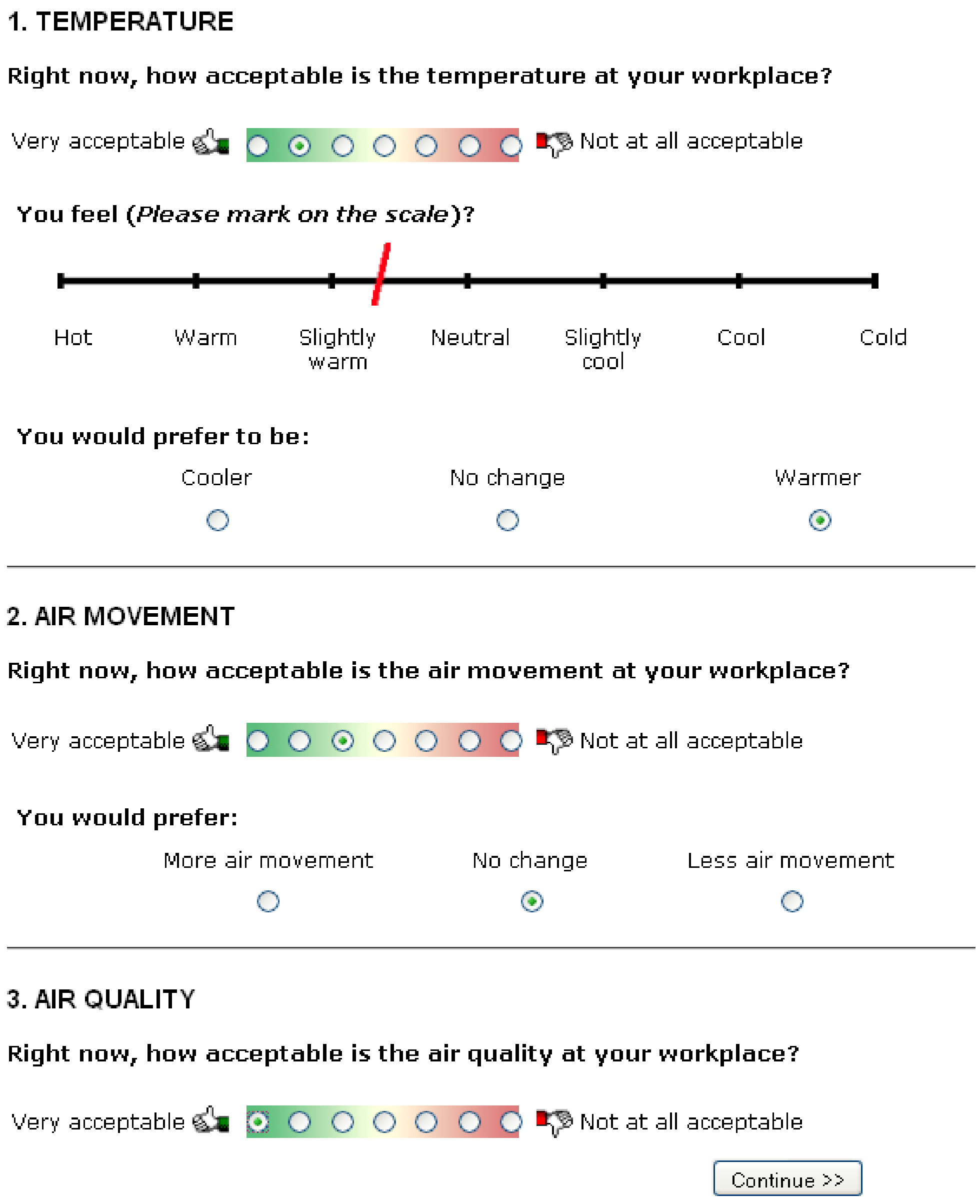
Appendix

a. Alameda study questionnaire



1. TEMPERATURE

Right now, how acceptable is the temperature at your workplace?

Very acceptable — Not at all acceptable

You feel (*Please mark on the scale*)?

Hot | Warm | Slightly warm | Neutral | Slightly cool | Cool | Cold

You would prefer to be:

Cooler | No change | Warmer

2. AIR MOVEMENT

Right now, how acceptable is the air movement at your workplace?

Very acceptable — Not at all acceptable

You would prefer:

More air movement | No change | Less air movement

3. AIR QUALITY

Right now, how acceptable is the air quality at your workplace?

Very acceptable — Not at all acceptable

Continue >>

4. NOISE LEVEL

Right now, how acceptable is the noise level at your workplace?

Very acceptable ○ ○ ○ ○ ○ ○ ○ Not at all acceptable

Please rate the noise from.....

	Not disturbing	Slightly disturbing	Moderately disturbing	Very disturbing
...people's conversations, phones, etc.				
...ceiling or desk fans				
...office equipment				
...outside				
...other				

Please specify

If you have additional comments, click here

5. CLOTHING

Please mark in the list below all the garments you are wearing now.

- ☐ Short-sleeved shirt or blouse 
- ☐ Sweater or jacket 
- ☐ Long-sleeved shirt or blouse 
- ☐ Tie 
- ☐ Shorts 
- ☐ Trousers, pants 
- ☐ Skirt or dress 
- ☐ Sandals or open-toed shoes 
- ☐ Shoes, sneakers, or boots 

Continue >>

b. Jaipur study questionnaire

THERMAL COMFORT QUESTIONNAIRE SURVEY-2011

[Survey No.] [Surveyor's Name: _ _ _ _ _ _ _ Building/office Name: _ _ _ _ _ _ _ _ _ _]

Part-A (To be filled by occupant)

1. **Occupant name :** _
2. **Occupant designation** : **BTech/ M.Tech/ PhD** **year of study:** 1^{st} / 2^{nd} / 3^{rd} / 4^{th}
3. **Room No. and floor:** _
4. **Date:** / /2013 **5. Time:** _ _:_ _
6. **Gender** ☐ Male ☐ Female
7. **Weight :** _ _ _ _ _ _ _kg **8. Height:** _ _ _ _ft **9. Age :**_ _ _ _ yr
10. **Name of your native place:** _
11. **Residing years in present city:**
   ☐ One year ☐ two years ☐ three years ☐ more than 3 years
12. **Year of service/work on current designation/position:**
   ☐ One year ☐ two years ☐ three years ☐ more than 3 years
13. On the basis of **temperature** how do you feel right now?
   Cold ☐ Cool ☐ Slightly Cool ☐ Neutral ☐ Slightly warm ☐ Warm ☐ Hot ☐
14. On the basis of **humidity,** how do you feel right now?
   Very dry ☐ Moderately dry ☐ Slightly dry ☐ Neutral ☐ Slightly humid ☐ Moderately Humid ☐ Very humid ☐
15. On the basis of indoor **air movement,** how do you feel right now?
   Very still ☐ Moderately still ☐ Slightly still ☐ Acceptable ☐ Slightly Moving ☐ Moderately Moving ☐ Much Moving ☐
16. On the basis of **combined effect of above three,** how do you feel right now?
   Very comfortable ☐ Comfortable ☐ Slightly comfortable ☐ Uncomfortable ☐ Very uncomfortable ☐
17. If you could choose to change, how would you prefer the **temperature** to be?
   Much cooler ☐ A bit cooler ☐ No change ☐ A bit warmer ☐ Much warmer ☐
18. If you could choose to change, how would you prefer the **humidity** to be:
   Moderately dry ☐ Slightly dry ☐ No change ☐ Slightly humid ☐ Moderately Humid ☐
19. If you could choose to change, how would you prefer the air velocity to be:
   Moderately still ☐ Slightly still ☐ No change ☐ Slightly Moving ☐ Moderately Moving ☐
20. **Sensation of lighting:** How do you find the lighting level?
   Very Bright ☐ Bright ☐ Slightly Bright ☐ Neither bright nor Dim ☐ Slightly Dim ☐ Dim ☐ Very Dim ☐
21. What would you prefer lighting level?
   Much dimmer ☐ A bit dimmer ☐ No change ☐ A bit brighter ☐ Much brighter ☐

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22. In the last one hour what are the changes made by you (if no changes please check mark☐)?

	Window	Door	Fan	Evaporative cooler	Air conditioner
Open/On (√)					
Close/Off (√)					

23. Your activity in last 15 minutes (Please tick):

Activity	(√)	Duration (hours)	Activity	(√)	Duration (hours)
Sleeping	☐	☐	Standing (working)	☐	☐
Sitting (passive work)	☐	☐	Walking indoors	☐	☐
Sitting (active work)	☐	☐	Walking outdoors	☐	☐
Standing relaxed	☐	☐	Others (Specify)……………………………..		

24. What are you wearing now? (select from list)

1	Baniyan		13	Tights	
2	T-shirt		14	Pyjamas	
3	Short sleeve shirt (Poly/cotton)		15	Lower (thermal inner)	
4	Long sleeves shirt (Poly/cotton)		16	Dhoti	
5	Cotton sari, blouse		17	Jeans	
6	Polyester sari & blouse		18	Trousers/long skirt (Poly/cotton)	
7	Cotton salwar kameez		19	Shorts/short skirt (Poly/cotton)	
8	Polyester salwar & kameez		20	Long gown	
9	Jacket/woolen jacket		21	Scarf/Woolen Cap/hat	
10	Pullover/Sweater/ upcollar		22	Sandals	
11	Thermal tops		23	Slipper	
12	Suit		24	Socks & shoes	

25. Do you feel local thermal discomfort at any part of your body (please tick):

Neck/Head	☐	Arms	☐
Back	☐	Feet	☐
Chest	☐	Palms	☐
No	☐		

26. Do you use **air conditioner/heater at home?**

Yes / No If yes (no. of years):

27. Do you use **A/C or heater in car?**

Yes / No If yes (no. of years):

Any comments about survey: - . . . .

Thank you so much ………………….

Signature (optional)

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Part-B (To be filled by Surveyor)
MEASUREMENTS AT OCCUPANT LOCATION

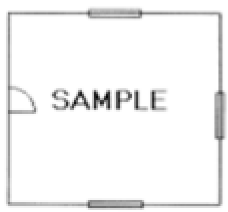
Date: _ _/_ _/_ _ _ _ **Time:** _ _:_ _

1. Kind of office:-
- a) Individual office room ☐
- b) Shared / open plan office ☐

2. Nature of building
- a) Glazed building ☐
- b) Traditional building ☐
- c) Green/Certified building ☐
- d) Any other:-

3. Please mark position of **Person-'X'**, **Fan-'F'**, **AC-'A'** and **'H'-for any heat source** with respective location in the given sample)

WWR- **E / UE**



WWR- **E / UE**

WWR- **E / UE**

'E'-Exposed wall, 'UE'-Unexposed wall,
'WWR'-Window wall ratio

4. Level of physical **activity**:
(Please tick)
- ☐ Reclining
- ☐ Seated Quite
- ☐ Office, School
- ☐ Standing Relaxed
- ☐ Light Activity, Standing
- ☐ Medium Activity, Standing
- ☐ High Activity

5. Air draft hitting to the occupant:
Yes / No

6. Glazing type:

Single pane glass	Single Tinted	Single reflective	Double pane	Special Glass Low–SHGC, low-e	Others
☐	☐	☐	☐	☐	☐

7. Roof: ☐ Exposed ☐ Unexposed

8. Control conditions during survey:-

	Open (√)	Close (√)		On (√)	Off (√)
External door			Fan		
Balcony door			Lights		
Window					
Blind/ curtain					

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9. Air conditioning system in the surveyed room: Please check mark the (√) the following:

System	Split-AC/Heater	Window-AC/heater	Central air conditioning	Evaporative coolers	Central Evap. cooler	Fan operated /Any Others
Type of cooling/heating system used						
Height of Cooling /heating system (ft)						
How long use of particular type (years)						

10. Distance of window from working station

☐ 0.5m ☐ 1m ☐ 1.5m ☐ Not near window

11. Thermostat setting – _ _ _ _ _°C **12. No of occupants:**

13. Lighting level: Lux ....

14. Seasonal Conditions

☐ winter ☐ Spring ☐ Summer ☐ Fall

15. Sky conditions: ☐ Clear ☐ Mixed ☐ Cloud

16. Environment conditions:

Sr. no	Environment variables	I (close to person)	II (close to person)
I	Outdoor temperature-°C		
II	Room air temperature -°C		
III	Relative humidity -%		
IV	Mean radiant temperature °C		
V	Air velocity -m/s		

17. Level of $\mathbf{CO_2}$ ☐ ppm

18. Qualification of surveyed person- ☐ Metric ☐ G ☐ PG

19. Approximate annual income (lac)- ☐ 2-5 ☐ 5-10 ☐ more than 10

Thank you so much for cooperation. Your views and observations are very valuable to us. If anything remains left from our approach we look forward your valuable suggestions.

Symbols-
G-Graduate, PG-Postgraduate

....
Signature (optional)

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