Proceedings of 8th Windsor Conference: ***Counting the Cost of Comfort in a changing world*** Cumberland Lodge, Windsor, UK, 10-13 April 2014. London: Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Visualizing the results of thermal comfort field studies: putting publicly accessible data in the hands of practitioners

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Abstract

Large sets of thermal comfort field data have been analysed in detail to inform generalized thermal comfort standards, but there is specific information that might be relevant to particular projects that is not easily accessed by practitioners. We developed interactive tools that allow users to explore the data and look at the subsets that are most interesting to them because of location, culture, building type, etc. The first tool displays curves of dissatisfaction percentages for ranges of thermal sensation, PMV, and indoor temperature based on the comfort metrics of acceptability, comfort, and sensation. Using this tool, we show that a thermal sensation range of -1.3 to 1 provides 80% satisfaction based on acceptability and comfort in both naturally ventilated and air conditioned buildings. The second tool provides a new way of analysing and representing data in these datasets that calculates satisfaction percentage directly, and visualizes the results clearly. We demonstrate how the interactivity allows users to answer project-specific questions. While our visualization method is helpful for displaying the data, it does not provide a mathematically defined comfort zone. We discuss future avenues of development of these tools.

Keywords: thermal comfort, data visualization

1 Introduction

The goal of ASHRAE Standard 55 is to define the conditions under which at least 80% of a building's occupants will be satisfied with the thermal environment. In the case of naturally ventilated (NV) buildings, these conditions are described by the adaptive model, which indicates comfortable indoor temperatures based on monthly mean or running mean outdoor temperature (ANSI/ASHRAE, 2013).

Although the final adaptive model is given in terms of indoor and outdoor temperature and percent satisfaction, the fundamental steps for deriving it also included thermal sensation. Using a large database of thermal comfort field studies, de Dear and Brager found the neutral temperature for each building during each season by calculating a linear regression between indoor temperature and thermal sensation. These neutral temperatures and their associated mean monthly outdoor temperatures were then plotted against each other, and the overall model was found by running a regression through these points. In order to determine the comfort zone, i.e. the deviations from the neutral temperature that still allow 80% satisfaction, they used the PMV-PPD relationship derived by Fanger from chamber studies (de Dear & Brager, 1998).

The European thermal comfort standard for naturally ventilated buildings also relates comfortable indoor temperatures to outdoor temperature, in this case defined as running mean (CEN, 2007). Although the details differ, McCartney and Nicol's analysis of the SCATs database was similar to de Dear and Brager's. They first calculated neutral comfort temperature based on a relationship between indoor temperature and thermal sensation and then ran a regression between comfort and running mean temperatures to develop their adaptive curve (McCartney & Nicol, 2002). To determine the range of comfortable temperatures, they relied on Fanger's assumption that thermal sensations of -1, 0, and 1 indicate satisfaction and plotted the proportion of people who were satisfied with the thermal conditions as a function of the difference between the actual temperature and the neutral temperature. The deviations from the neutral temperature that were included in the standard are based on 15%, 25%, and 35% dissatisfaction, although the dissatisfaction percentages are not mentioned in the standard (Fanger, 1982; Nicol & Humphreys, 2010; CEN, 2007).

In both these cases, the desired relationship is between indoor and outdoor temperature, but it is mediated by thermal sensation in finding a neutral or comfort temperature. Outdoor temperature is only introduced as a secondary step.

The data from numerous thermal comfort field studies around the world is publicly available in the ASHRAE RP-884 database. The European-based SCATs database has not been publicly available to date, but we were given access to it, and there are plans to make it publicly available soon. Both of these databases have been analysed in detail to inform generalized thermal comfort standards, but there is specific information that might be relevant to a particular project that is not easily accessed by practitioners.

The goal of this project is to

- Determine the range of thermal sensation votes that indicate satisfaction.
- Develop a method of visualizing and identifying a comfort zone directly using thermal comfort or thermal acceptability metrics, when available, rather than by way of thermal sensation and neutral temperature.
- Create interactive tools to provide practitioners with easy and useful access to publicly available thermal comfort field data, so they can conduct their own analysis.

2 Methods

This project is based on thermal comfort field study data from the ASHRAE RP-884 and SCATs databases as well as two separate studies in the San Francisco Bay area (de Dear & Brager, 1998; McCartney & Nicol, 2002; Brager et al., 2004, Zhang et al., 2007; Linden et al., 2014). The aggregated database contains 32,055 observations from 169 buildings in 11 countries; 148 of the buildings are offices, and the others include houses, schools and factories. About half of the observations come from naturally ventilated (NV) buildings, which are the ones we focus on in this paper. The remaining half come predominantly from air conditioned (AC) buildings, but there are also some from mixed-mode (MM) buildings. All of the respondents were asked to rate their thermal sensation on the 7-point ASHRAE scale. In 70 buildings (38% of observations), respondents were asked about thermal acceptability, and in 97 (45%) they were asked about overall thermal comfort.

First we examine which votes represent "satisfied", since most field studies don't ask directly about satisfaction with the thermal environment. Instead, researchers look to questions about thermal sensation, acceptability, preference, and comfort to assess satisfaction (Arens et al., 2010; Zhang et al., 2011). Thermal sensation is the most widely reported response, so it is a very useful metric to use. But it is not clear what range of sensation should be considered satisfied. Fanger assumed that individual thermal sensation votes of -1, 0, and 1 indicated satisfaction and used probit analysis to derive the PMV-PPD relationship from that. Although de Dear and Brager did not explicitly define a satisfied range of thermal sensation for individual votes, they did so implicitly by calculating the 80% satisfaction limits based on an average thermal sensation of ±0.85. This value comes from the PMV-PPD curve and has not been justified with field data by directly comparing thermal sensation and comfort or acceptability votes (de Dear & Brager, 1998; Fanger, 1982). Nicol and Humphreys explicitly accepted this assumption in deriving the limits of the three classes of thermal comfort for EN 15251 (Nicol & Humphreys, 2010).

We utilize studies that asked questions about acceptability or comfort in addition to sensation in order to determine an appropriate range of thermal sensation. Following the methodology that Fanger used to develop the PMV-PPD curve, we use probit analysis to predict the percentage of dissatisfied votes (Fanger, 1982). However, we use individual thermal sensation votes instead of PMV. Probit models fit s-shaped curves to systems with a dependent variable that has two possible values. In this case, we fit separate probits to votes that are dissatisfied because of being too hot and too cold. The total dissatisfaction percentage is the sum of the hot and cold dissatisfied percentages. We divide the data into satisfied and dissatisfied based on acceptability or comfort and then use thermal sensation to determine whether the person was hot or cold. The tool calculates the appropriate probits for three different comfort metrics (sensation, comfort, acceptability) and three different independent variables (sensation, PMV, indoor temperature).

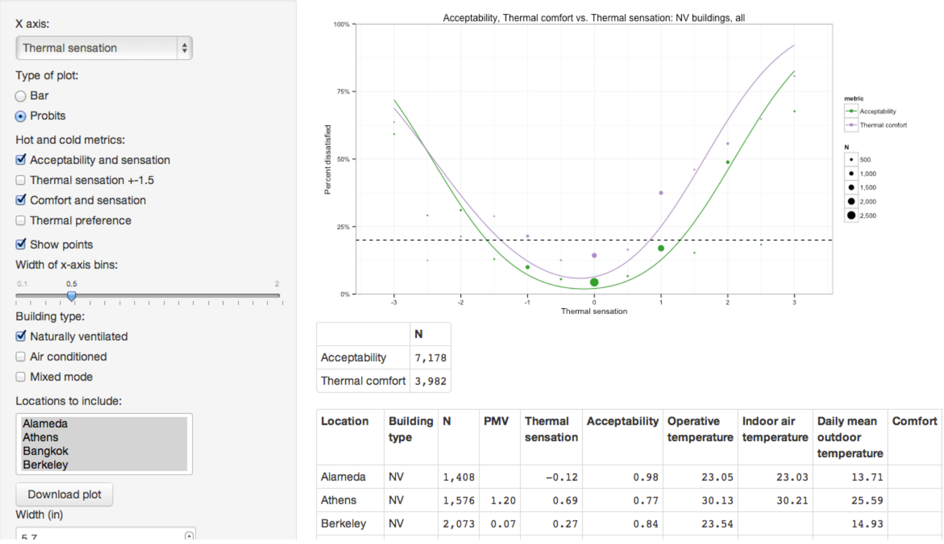
Adaptive comfort standards relate comfortable indoor temperatures to outdoor temperature. In order to visualize satisfaction in this framework, we bin thermal comfort votes according to the indoor and outdoor temperature conditions under which they were given. Then within each two-dimensional bin we calculate the percentage of satisfied votes. For acceptability, comfort, and the common assumption of ±1 thermal sensation, the satisfaction percentage is calculated by counting the number of satisfied votes and dividing by the total number of votes in each bin. However, this method cannot be applied to the relationship derived using the probit analysis because individual thermal sensation votes are not sure to indicate satisfaction or dissatisfaction. In other words, someone recording a thermal sensation of +1 will be satisfied only 80% of the time and so cannot be counted as satisfied (Figure 3a). So instead of counting satisfied votes in each bin, we convert each thermal sensation vote to its probability of having a coincident "acceptable" vote and average those probabilities. An accumulation of bins with at least 80% satisfaction delineate the comfort zone.

3 Results

We developed two interactive visualization tools that give practitioners and researchers an easy way to select subsets of thermal comfort field study databases that are interesting to them (Figure 4). The tools are built with the statistical package R, using the "ggplot2" library for visualization and the "shiny" library as the interface between R and html (R Core Team, 2013; Wickham, 2009; RStudio Inc., 2013). The user interface has dropdown menus, sliders, and input fields that allow users to filter the overall database based on the building location, cooling strategy, and program. Users can choose the metrics for the axes and for calculating satisfaction, the width of the bins, and the minimum number of votes that are required in a bin for it to be displayed. The screen then gives them immediate feedback, visualizing the results based on the input parameters and filters. In addition to the graph, there is a data table that indicates the sources of the data and the mean values of the basic physical and survey responses for each city that is included.

3.1 Percent dissatisfaction tool

This tool uses probit analysis to display the percentage of dissatisfied votes as a function of a variety of metrics - thermal sensation, PMV, or indoor temperature - and plots the corresponding probits. The four metrics for calculating satisfaction (or conversely, dissatisfaction) are acceptability, thermal sensation, comfort, and preference (**Figure 1**).


X axis: Thermal sensation

Type of plot:
○ Bar
● Probits

Hot and cold metrics:
☑ Acceptability and sensation
☐ Thermal sensation +-1.5
☑ Comfort and sensation
☐ Thermal preference

☑ Show points

Width of x-axis bins: 0.5

Building type:
☑ Naturally ventilated
☐ Air conditioned
☐ Mixed mode

Locations to include:
Alameda
Athens
Bangkok
Berkeley

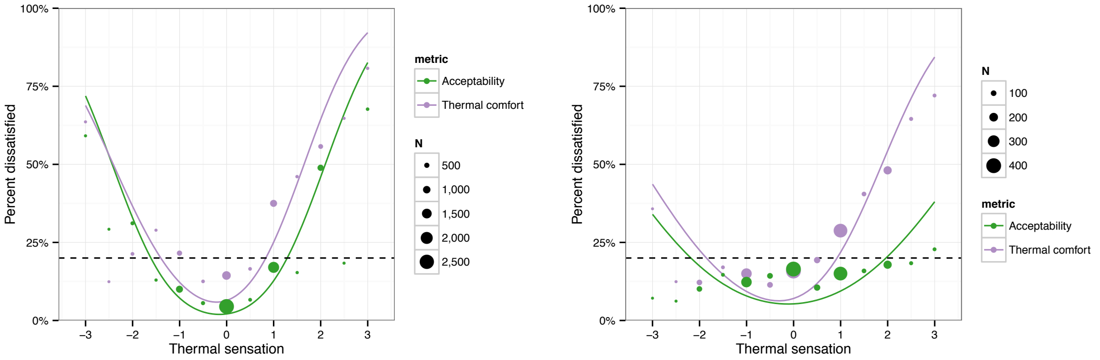
	N
Acceptability	7,178
Thermal comfort	3,982

Location	Building type	N	PMV	Thermal sensation	Acceptability	Operative temperature	Indoor air temperature	Daily mean outdoor temperature	Comfort
Alameda	NV	1,408		-0.12	0.98	23.05	23.03	13.71	
Athens	NV	1,576	1.20	0.69	0.77	30.13	30.21	25.59	
Berkeley	NV	2,073	0.07	0.27	0.84	23.54		14.93	

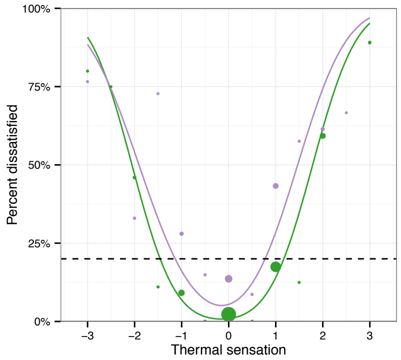
Figure 1. Screenshot of probit analysis tool

To determine a reasonable range of thermal sensation that can be considered satisfactory, we used this tool to analyze the results of those studies that asked acceptability and/or general comfort questions in addition to a sensation question. **Figure 2**a shows the probit curves for NV buildings using acceptability and comfort. We were surprised that they showed only about 65% dissatisfaction at a thermal sensation of -3, so we looked through the probits for individual cities to see if we could see why. We found that in Honolulu, only 10% of people rated -3 thermal sensation as being unacceptable and only 40% rated it as being uncomfortable (**Figure 2**b, dots). We concluded that these results might be because they are from school children, so we excluded Honolulu from further analysis. **Figure 2**c shows the result without the buildings in Honolulu. We describe these steps as an illustration of the benefits of this interactive tool, which makes all of these steps of the analysis quick and easy to do.

In all of these graphs, the comfort metric results in a slightly narrower range of thermal sensation that provides a given level of satisfaction than the acceptability metric does (**Figure 2**c). These results cannot be compared directly to Fanger's assumption that sensations of -1, 0, 1 are comfortable and that other sensations are not, since it indicates that there are no sensations that guarantee 100% comfort or discomfort.



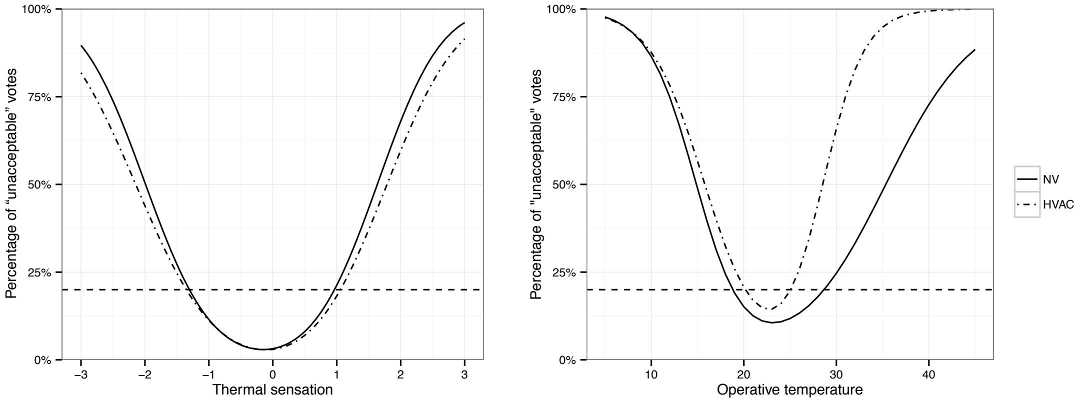
a. All NV buildings b. Only NV buildings in Honolulu



c. NV buildings without Honolulu

Figure 2. Dissatisfaction vs. thermal sensation for NV buildings

Figure 3a compares the probit curves of dissatisfaction based on acceptability vs. thermal sensation for NV and AC buildings. They are virtually identical, particularly for dissatisfaction less than 20%, but also across the whole range of thermal sensation. However this does not mean that the physical conditions that correspond to these sensations and levels of satisfaction are the same for both types of buildings. In fact, the range of operative temperatures that provide 80% satisfaction is about 18-28 °C for NV and only 20-25 °C for AC buildings. Beyond these ranges, the dissatisfaction percentage for NV buildings is up to 30 percentage points below that of AC buildings for the same temperature (**Figure 3**b).

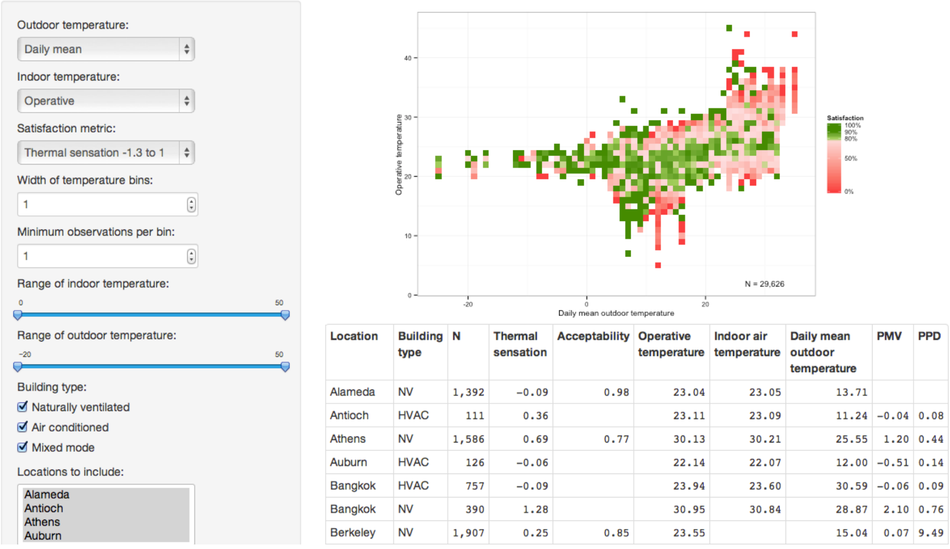


a. Thermal sensation b. Operative temperature

Figure 3. Dissatisfaction based on acceptability: comparison of NV and AC buildings excluding Honolulu

3.2 Satisfaction mapping tool

This tool visualizes comfortable indoor environmental conditions mapped against outdoor temperature. It follows the convention of ASHRAE 55 and EN 15251 and puts indoor temperature on the y-axis and outdoor temperature on the x-axis. Depending on the source of the data, outdoor temperature is either monthly mean or running mean and therefore is referred as "prevailing outdoor temperature". Satisfaction (comfort) is represented by color, with percentages above 80% being green. The user can choose which metric is used to calculate satisfaction (**Figure 4**).



Outdoor temperature: Daily mean

Indoor temperature: Operative

Satisfaction metric: Thermal sensation -1.3 to 1

Width of temperature bins: 1

Minimum observations per bin: 1

Range of indoor temperature: 0 – 50

Range of outdoor temperature: -20 – 50

Building type:

☑ Naturally ventilated

☑ Air conditioned

☑ Mixed mode

Locations to include:

Alameda

Antioch

Athens

Auburn

Location	Building type	N	Thermal sensation	Acceptability	Operative temperature	Indoor air temperature	Daily mean outdoor temperature	PMV	PPD
Alameda	NV	1,392	−0.09	0.98	23.04	23.05	13.71		
Antioch	HVAC	111	0.36		23.11	23.09	11.24	−0.04	0.08
Athens	NV	1,586	0.69	0.77	30.13	30.21	25.55	1.20	0.44
Auburn	HVAC	126	−0.06		22.14	22.07	12.00	−0.51	0.14
Bangkok	HVAC	757	−0.09		23.94	23.60	30.59	−0.06	0.09
Bangkok	NV	390	1.28		30.95	30.84	28.87	2.10	0.76
Berkeley	NV	1,907	0.25	0.85	23.55		15.04	0.07	9.49

Figure 4. Screenshot of visualization tool

Figure 5 shows indoor-outdoor temperature bins that provide 80% satisfaction for NV buildings based on acceptability votes. From this visualization, the upward trend of green bins makes it clear that acceptable temperatures vary depending on the daily mean outdoor temperature. However, only about half of the observations in NV buildings are displayed in this particular graph, because many field studies did not ask a question about thermal acceptability. This limitation pointed to the need for another kind of analysis.

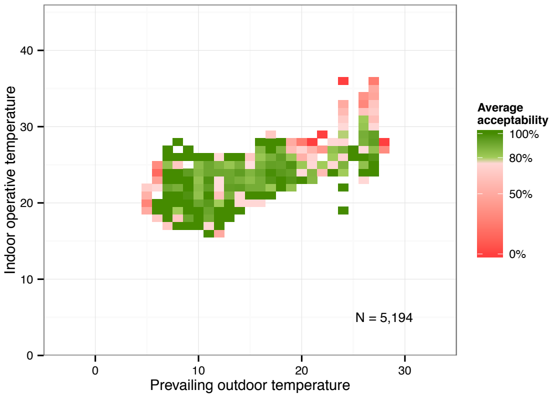
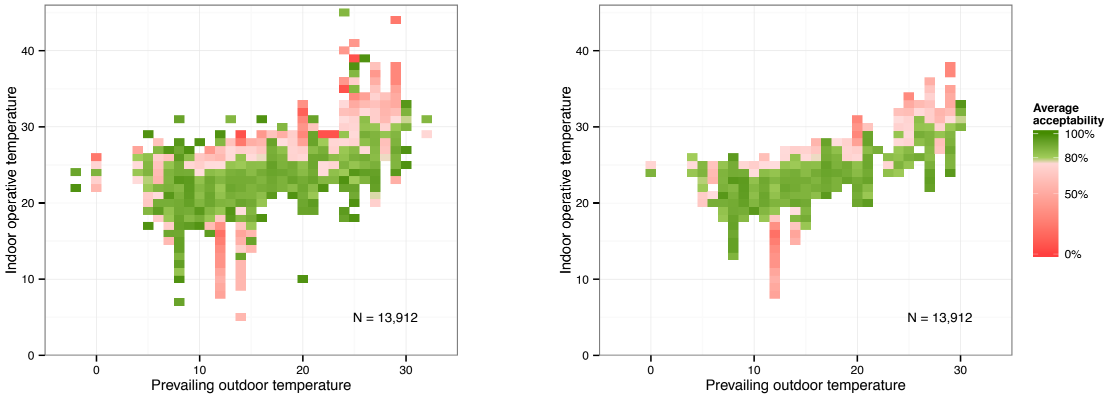


Figure 5. 80% satisfaction zones for NV buildings based on thermal acceptability

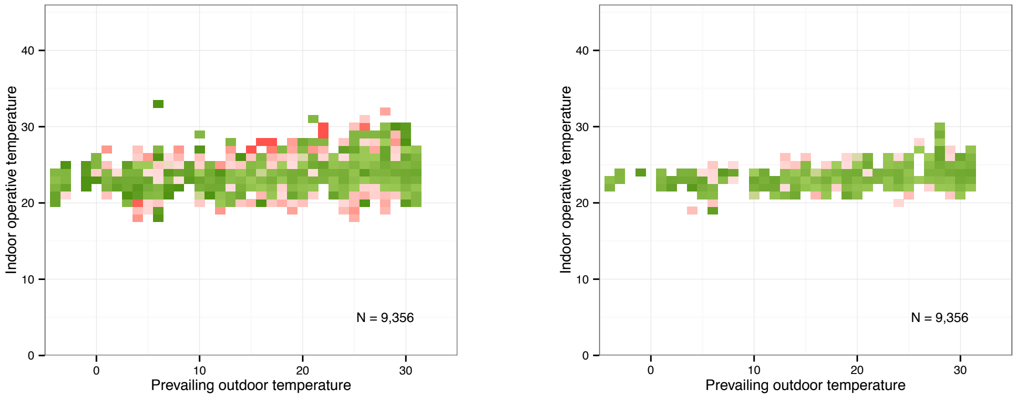
In order to use data from all of the studies, we use the relationship between thermal sensation and acceptability that we developed above (**Figure** 3a) to replot what we did in **Figure 5**. Because the green region is mostly bounded by red and pink, including all of the data defines the comfort zone a bit better (Figure 6a). From **Figure 5** it is not clear what the upper limit for indoor comfort temperature is for outdoor temperatures below 20 °C because the upper edge of the green region is not bounded by red. This problem is cleared up in **Figure 6**a, where the red region follows the upward slope of the green band.

The interactive tool allows users to explore the data in a variety of ways, depending on their interests or applications. Which results are we most confident about? Some of the bins have hundreds of observations and others only one, so we can use the filter to increase the minimum number of observations per bin (**Figure 6**b), and compare this to the results for all bins (**Figure 6**a). This shows that, in general, the bins at the upper and lower bounds of indoor temperature for each outdoor bin have fewer observations, so we are not as confident about their satisfaction rate as we are about other bins. Even so, the upper indoor temperature limit of 80% satisfaction (green squares) is reasonably well defined. One can also use the tool to ask - does it make a difference if the people are in NV or HVAC buildings? Selecting only the HVAC buildings shows that votes were cast in a narrower range of indoor temperatures and that indoor and outdoor temperatures are not strongly related. This is what we would expect in these buildings. A new contribution that this visualization method provides is that it shows that the width of the comfort zone is smaller and more well defined in HVAC than NV buildings because there are dissatisfied regions above and below the green band (**Figure 6** c&d).



a. All NV buildings, all bins

b. All NV buildings, bins with at least ten votes



c. AC buildings, same outdoor temperature range, all bins

c. AC buildings, same outdoor temperature range, bins with at least ten votes

Figure 6. 80% satisfaction zones based acceptability vs. sensation probit analysis

Based on this exploration of the thermal comfort field data, a designer can approach her analysis of her project with fresh eyes. For example, if energy simulation indicated that the operative temperature sometimes fell to 20 °C inside her proposed building, she is likely to be more concerned if her project has air conditioning than if it does not. In HVAC buildings there is a relatively consistent red line around 20 °C but in NV buildings the lower edge of the comfort zone is left largely undefined (**Figure 6** c&d). While this graphical analysis cannot supplant comfort standards (see discussion below), it helps designers put energy simulation results into context.

4 Discussion

The probit analysis that we conducted relating thermal acceptability and comfort votes to thermal sensation provides an evidence-based range of thermal sensation that can provide 80% satisfaction. The results are similar to Fanger's estimate that the middle three thermal sensation categories (-1, 0, 1) represent thermal satisfaction (Fanger, 1982). Because Fanger was using an integer scale, other researchers have adapted the satisfaction range to be -1.5 to 1.5 when using continuous scales (de Dear & Brager, 1998). Our analysis indicates that the range is somewhere in between, but it is unclear how much this is being affected by the fact that many of the studies used integer scales of sensation.

The related tool is a convenient way of exploring the data, as we described above using the example of Honolulu. The danger with such quick statistical analysis, however, is that it's easy to see a curve and come to quick conclusions that may not be justified. For example, only about 3% of the acceptability votes in HVAC buildings occurred under conditions with PMVs outside of the -1 to 1 range. However the tool will fit a probit to this data without giving any indication that the outer ranges of this curve are much less certain than the inner region. To help combat this, we are working on displaying a confidence interval in addition to the simple probit curves.

Our method of visualizing the comfort zone by calculating the percentage of satisfied votes for combinations of indoor and outdoor temperature has both advantages and disadvantages. The best thing about it is that the raw data is translated very directly to the desired information of satisfaction percentage in areas of indoor-outdoor temperature space. This means that we can include data that does not produce a statistically significant regression or we can look at all data without making assumptions about the relationship between thermal sensation and indoor temperature (de Dear & Brager, 1998; McCartney & Fergus Nicol, 2002). Although there is still some uncertainty about how best to define satisfaction, we improve on previous methods by deriving rather than assuming a relationship between thermal sensation and acceptability.

Another advantage of this method is that the visualization technique can be used for small datasets. When no statistical analysis is performed, whatever data is available can be displayed without making assumptions about areas around it where there are no observations. This means that researchers and practitioners can quickly look at and compare subsets of the overall data. While the adaptive model accounts for climatic differences by including outdoor temperature (daily, monthly, running mean), it does not differentiate between cultures, building types, the kinds of adaptive opportunities are available, etc. Using this tool, it is possible to consider only those studies that are most relevant to the project of interest. This is a particular advantage for mixed mode (MM) buildings because there are not very many studies that have been conducted in them.

A significant disadvantage of this method is that it does not give a well defined comfort zone, which makes it less useful for standards and quantitative analysis. We are exploring various machine learning and classification techniques, such as support vector machines and expectation maximization algorithms, to see if they can help overcome this disadvantage.

5 Conclusion

This new way of looking at satisfaction percentages in small bins that are defined by both indoor and outdoor temperature directly evaluates the parameters that are important for the adaptive model and presents them in an easily understandable manner. By allowing users to filter the dataset and get immediate results, the tool we developed can display only the information that is relevant to a particular project. Because this information might be limited and depend on a small sample size that does not allow valid statistical analysis, the fact that this tool is primarily for visualization is an advantage.

This tool is still under development. We hope to allow filtering on more parameters (e.g. presence of operable windows or ceiling fans, the clothing or metabolic rate of the respondents, climate zone) and in a more well implemented way that only displays the combinations that have data available. We want to explore other ways of conducting statistical analysis that builds on this approach of considering satisfaction rates in 2D temperature bins. Eventually, once the tool is further refined, the intention is to make it publicly available on the internet.

Acknowledgement

This study, "Natural ventilation for energy saving in California commercial buildings," (project 500-10-025) was funded by the California Energy Commission (CEC).

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