Predicting Thermal Comfort Level through Environmental Factors in an Office Setting

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ABSTRACT
Studies have shown that thermal comfort and productivity in an office setting are linked to one another. Therefore, in order to maximize production of inhabitants a building should look to optimize their thermal comfort level. The challenge is identifying what drives thermal comfort. Using regression trees this paper tests the ability of environmental variables to predict the thermal comfort level of an inhabitant. This paper also tests to see how much of thermal comfort can be explained by personal preference.

1. INTRODUCTION
An air conditioned office building is designed to provide a thermally acceptable environment for human comfort and work, that would enhance the productivity and reduce thermal dissatisfaction.[1] Better indoor climate conditions guarantee potential monetary gains due to improvement in workers' productivity. Various studies have estimated the potential annual gain of productivity increase due to the reduction of respiratory infection to be equivalent to $6 to 14 billion, while a reduction of sick building syndromes (SBS) could yield around $15 to 38 billion.[2][3] Most significantly, improved working efficiency could yield $20 to 200 billion.[2][3] Therefore thermal comfort, which is a state of mind that expresses satisfaction with the thermal environment (ASHRAE Standard 55)[4], is of utmost importance while designing an office building. Thermal comfort is a fluid concept and varies from person to person. It is influenced by the cumulative effect of six primary factors – air temperature, humidity, velocity of air, mean radiant temperature, clothing level and metabolic rate.[5]

As such, guaranteeing thermal comfort to building inhabitants is of key importance to building management. The challenge is identifying what drives thermal comfort in order to determine the best strategy to manage it. The purpose of this paper is to see if thermal comfort levels inside an office environment can be predicted by environmental factors alone through the utilization of regression trees. Environmental factors considered for this study were indoor and outdoor temperature, relative humidity, and air velocity.

2. DATASET
Dataset used for the study is a result of data collection from data loggers and a longitudinal study that were used to analyze human-building interaction at Friends Center in Center City, Philadelphia, PA.[6] For the survey the following question areas included were - demographic information, office characteristics, thermal comfort and preferences, control options, personal values, and typical work schedules. A total of 45 occupants' responses were recorded, and based on a non proportionate quota sampling strategy, that looked to achieve at least ⅓ of the final sample in one of the key groupings (gender, office type, and location), a final sample of 24 occupants was sampled. The occupants filled an online survey every day for the next year, that asked them for subjective and objective measurements of thermal comfort. Thermal comfort was measured on a scale of 1 to 6, where 1 was "very uncomfortable" and 6 indicated that a participant was "very comfortable." Alongside, a data logger continuously recorded the local indoor environment around each occupant, the weather and the occupant's behavioral actions. Table 1 showcases a summary of the measurements recorded by data logger over the year. The dataset contains values of the controllable and uncontrollable variables over a period of one year starting July 2012.

Table 1: Summary of datalogger measurements of environment.[6]

Variable type	Variable measured	Observed range during survey
Outdoor environment	Ambient temperature (°C)	10 [6, 18]
	Relative humidity (%)	55 [43, 74]
	Wind speed (m/s)	4.05 [2.70, 5.85]
Indoor environment	Ambient temperature (°C)	22.95 [21.60, 23.95]
	Ambient temperature (°C)	22.84 [21.72, 23.71]
	Relative humidity (%)	30.91 [25.74, 41.31]
	Globe temperature (°C)	23.08 [22.01, 23.93]
	Air velocity (m/s)	0.027 [0.026, 0.037]

3. PROPOSED APPROACH
We broke up our approach to this problem into two steps: exploratory analysis and modeling via regression trees. From the literature review the three main environmental quantities we focused on were ambient temperature, relative humidity, and air velocity. Since measurements for these quantities were taken both indoors and outdoors we investigated their relationship to understand how well climate-controlled the office building was. Next we explored the relationship between each quantity and general thermal comfort to visualize any trends that would aid our hypothesis.

We created two trees for the regression tree models. The first used indoor air temperature, air velocity, and relative humidity to predict general thermal comfort and the second only using occupant number as a feature. The premise of a regression tree is to create binary splits along the features such that at each leaf the variance, V_c, is minimized in order for the total sum of squared error, S, to be minimized for a tree, T (Eqn. 1).[7]

Equation 1. Total sum of squared error in a regression tree.

$$S = \sum_{c \in leaves(T)} n_c V_c$$

Where n_c represents the number of samples in leaf c.

4. RESULTS AND DISCUSSION

4.1 Exploratory Data Analysis

To start we explored how well climate controlled the office building was from outside conditions. Indoor and outdoor measurements were taken concurrently so we calculated the average absolute difference between the corresponding internal and external measurement. We hypothesized that if the average absolute difference was large that the outdoor measurement could be neglected because it implies the building is well climate-controlled, thus external climate factors play a negligible role in the indoor climate. Table 2 enumerates these measurements.

Table 2. Average absolute difference between indoor and outdoor measurement.

Environmental Factor	Avg. absolute diff.
Temperature	10.8 °C
Relative Humidity	24.7%
Air Velocity	4.75 m/s

The large average absolute difference was confirmed by visual inspection of the relationship between indoor and outdoor measurements as shown in Figure 1(a), 1(b) and 1(c).

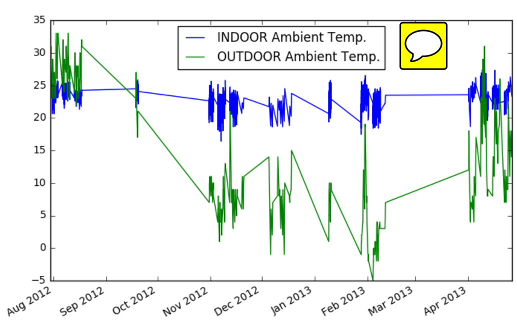

Figure 1(a) Visualization of indoor/outdoor relationship of ambient temperature.

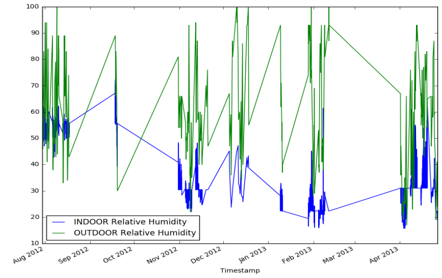

Figure 1(b) Visualization of indoor/outdoor relationship of relative humidity.

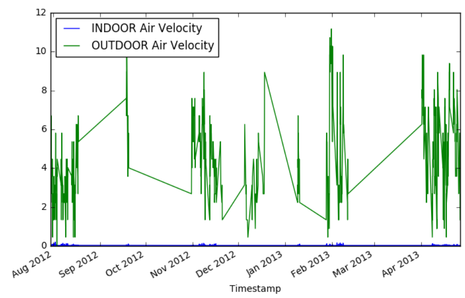

Figure 1(c). Visualization of indoor/outdoor relationship of air velocity.

The plots of each environmental variable reveal the relative stability of the indoor variables in comparison to their outdoor counterpart and any changes within in the indoor variable do not seem to be heavily influenced by the outdoor status. In conjunction with our average absolute difference measurements, which reveal a large difference in all three variables, we concluded that we could neglect outdoor measurements in our regression tree model.

Taking our three environmental variables to use for our regression tree, indoor temperature, relative humidity, and air velocity, we plotted each against the corresponding general thermal comfort level to see if any correlation could be visualized (Figure 2).

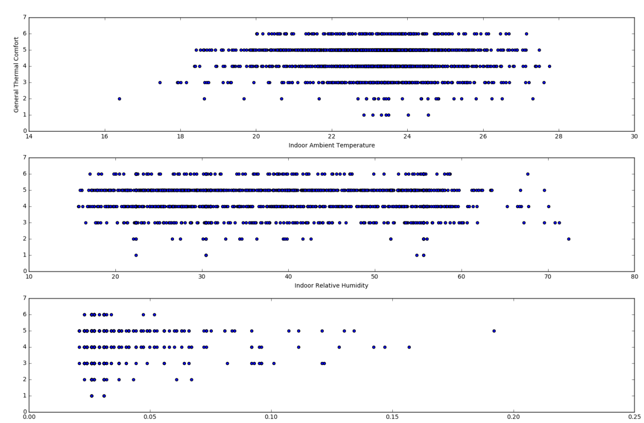

Figure 2. Thermal comfort versus environmental variables plots.

From looking at these scatter plots there appears to little to no relationship between the environmental variables and thermal comfort. To confirm this we calculated the correlation between each variable and general thermal comfort (Table 3).

Table 3. Correlation coefficients of environmental variables against general thermal comfort.

	General Thermal Comfort
Temperature	-0.05
Relative Humidity	-0.03
Air Velocity	-0.06

The correlation coefficients signify that there is essentially no relationship between environmental variables and general thermal comfort, validating our assertion from visual inspection of Figure 2. This also indicates that when a regression tree is run predicting general thermal comfort off the environmental variables it will have very little predictive power.

Since there is still variation in thermal comfort level at a given value for an environmental variable we theorized that this could be due to personal preference. From this analysis we decided to include a second regression tree to predict thermal comfort from occupant number.

4.2 Regression Tree Modeling

The first regression used indoor temperature, relative humidity, and air velocity as its features and general thermal comfort as the only response. As hypothesized during the exploratory analysis these variables had no predictive power over thermal comfort. The second regression tree using only occupant number as a feature recorded a low but much more significant R^2 value than the first tree (Table 4). Each tree was run one-thousand times and the average R^2 value computed to find a more accurate value.

Table 4. Average R^2 values for regression trees.

Features	**R^2 Value**
Environmental variables	-0.65
Occupant number	0.29

These results make sense in the context of our exploratory analysis because they demonstrate that thermal comfort is driven by personal preference when environmental variables are controlled for. As the plots in Figure 1 demonstrated the variance in environmental conditions was fairly low indicating that thermal comfort should have little variance if driven by environmental factors. However, in the subsequent plots (Fig. 2) we see that at any given temperature, humidity or air velocity there can be a large variance in thermal comfort.

Understanding the drivers for thermal comfort allows building managers to create strategies as to how to best optimize this. These results suggest that providing building inhabitants individual freedom to control their environment (i.e. providing them with a fan, dehumidifier, space heater, etc.) would be the best strategy to optimize thermal comfort and in doing so, productivity.

5. VALIDATION

In order to validate our regression tree results we split our dataset into train and test samples. The trained portion comprised 70% of the dataset while the test portion was 30%. A k-fold cross validation approach was attempted however the dataset was too small to make the scores of the folds meaningful.

6. FUTURE WORK

There is a large potential for future work in this area. Longitudinal survey data like is used here is both time- and cost-intensive so there is relatively little information out there currently. Research could be furthered by expanding the study to include more participants. This could increase the accuracy of the results via the larger sample size.

A second course of further study is to utilize more of the gathered data from this dataset. Many more survey questions were answered by participants regarding thermal preference, clothing level, etc. that could possibly be utilized to leverage new insights.

7. CONCLUSIONS

From this study we can conclude that personal preference plays a much larger role in determining thermal comfort than environmental variables in an office setting when the building is well climate-controlled. This is an important result for planning strategies to improve thermal comfort amongst building inhabitants. This study also affirmed that external environmental factors play no part in determining thermal comfort as they have little to no effect on the interior environment.

Non-mandatory participation in the daily surveys led to large gaps in the data that made it difficult to create an adequately large dataset from which to study. If this survey information were to be collected again gathering data from either a greater number of participants or with higher frequency could lead to both higher fidelity data and in turn clearer results.

8. ACKNOWLEDGMENTS

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