Evaluating Predictors of Thermal Comfort 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

In an office environment, maximizing productivity is imperative. Studies have shown that productivity is significantly impacted by the thermal comfort of the workers[1]. One such study estimated that improvement in indoor environment could lead to monetary gains ranging from $12 billion to $125 billion. Thermal comfort per ASHRAE, is a person's perceived satisfaction with their thermal environment. The six primary factors determining thermal comfort are air temperature, humidity, air velocity, clothing level, and metabolic rate. 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

The dataset used for the study was collected using data loggers and a longitudinal study meant 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 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 were selected. The occupants filled an online survey every day for the year of the study, which 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 (Mean [1Q, 3Q])
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]
	Relative humidity (%)	30.91 [25.74, 41.31]
	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. 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.

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 if the building was well climate-controlled. 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, the second only used occupant number as a feature.

4. RESULTS AND DISCUSSION

4.1 Exploratory Data Analysis

To start, we explored how affected indoor climate variables were by their outdoor counterparts. 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, the outdoor measurement could be neglected. This 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

To confirm that outdoor variables have negligible affects on indoor ones we plotted the indoor and outdoor values for each environmental factor against each other and calculated their correlation coefficients (Figure 1). These plots clearly show that outdoor air velocity and relative humidity have no effect on their indoor counterparts as their correlation coefficients are both almost zero. With a correlation coefficient of 0.52, outdoor temperature does have a weak relation to indoor temperature. However, as the plot shows, there is low variance in indoor temperatures indicating that the building temperatures are well controlled for over a much wider range of outdoor temperatures. The indoor temperatures only range from 16°C to 27°C whereas the outdoor temperatures range from -6°C to 34°C. Since both the average absolute differences and correlation coefficients indicate that the external environmental variables have minimal effect on the internal environmental variables, we will neglect them and only focus on the indoor variables in our regression tree model.

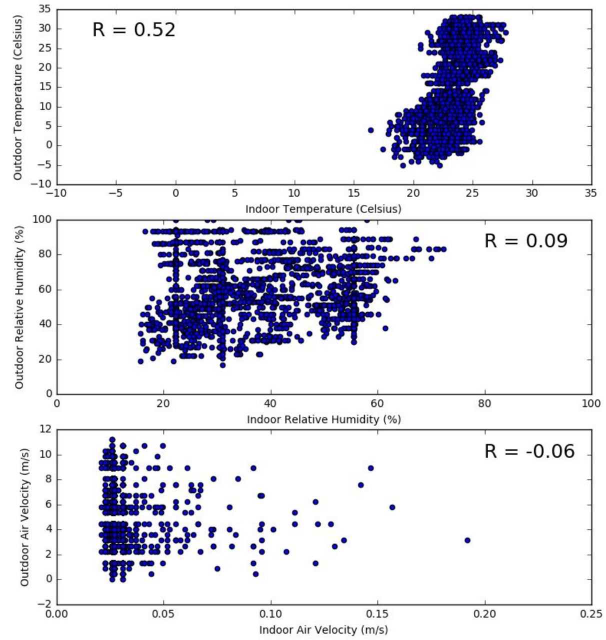

Figure 1. Visualization of indoor/outdoor relationship of environmental variables.

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).

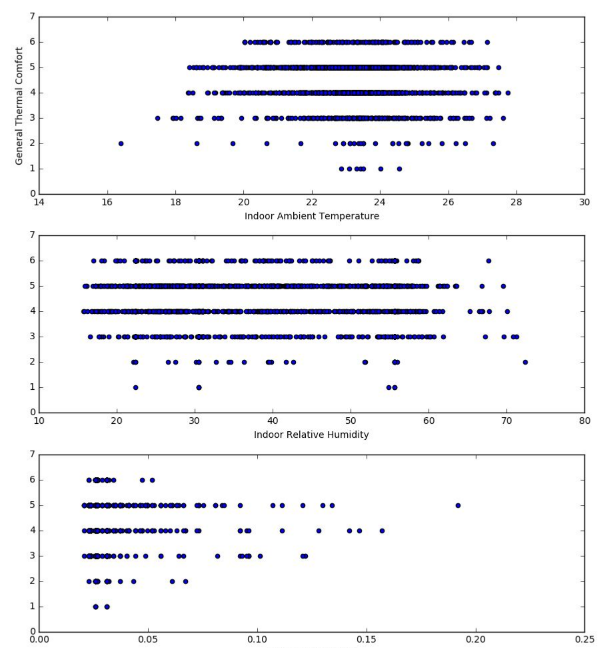

Figure 2. Thermal comfort versus environmental variables plots.

Observing these scatter plots, there appears to be little to no relationship between the environmental variables and thermal comfort. To confirm this, we calculated the correlation coefficient 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 a regression tree predicting general thermal comfort off the environmental variables 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. Due to this observation, we included a second regression tree to predict thermal comfort based solely on occupant number.

4.2 Regression Tree Modeling

The first regression tree 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. To achieve a more accurate result the average R^2 was computed after running each each tree one-thousand times (Table 4).

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 demonstrate 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 to optimize it. 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 much potential for future work in this area. Longitudinal survey data, as is used here, is both time- and cost-intensive so relatively little information has been produced at preseent. 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 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

Thanks to Mario Berges and Henning Lange for their guidance and assistance with this project.

9. REFERENCES

[1] Kosonen, R., & Tan, F. (2004). Assessment of productivity loss in air-conditioned buildings using PMV index. Energy and Buildings, 36(10), 987–993.

[2] W. Fisk, A. Rosenfeld. Estimates of improved productivity and health from better indoor environments. International Journal of Indoor Air Quality and Climate, 7 (1997), pp. 158–172

[3] W. Fisk, A. Rosenfeld. Potential nationwide improvements in productivity and health from better indoor environments. Proceedings of the 1998 Summer Study on Energy Efficiency in

Buildings, American Council for an Energy-Efficient Economy (1998)

[4] ANSI/ASHRAE Standard 55-2013, Thermal Environmental Conditions for Human Occupancy

[5] Atmaca, I., Kaynakli, O., & Yigit, A. Effects of radiant temperature on thermal comfort. Building and Environment, 42, 3210–3220.

[6] Langevin, J., Gurian, P. L., & Wen, J. (2015). Tracking the human-building interaction: A longitudinal field study of occupant behavior in air-conditioned offices. Journal of Environmental Psychology, 42, 94–115.

[7] Carnegie Mellon University Statistics Department (2006). Lecture 10: regression trees.