Statistical Analysis of Unsolicited Thermal Sensation Complaints in Commercial Buildings

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ABSTRACT

Unsolicited complaints from 23,500 occupants in 690 commercial buildings were examined with regard to absolute and relative frequency of complaints, temperatures at which thermal sensation complaints (too hot or too cold) occurred, and response times and actions. The analysis shows that thermal sensation complaints are the single most common complaint of any type and that they are the overwhelming majority of environmental complaints. The analysis indicates that thermal sensation complaints are mostly the result of poor control performance and HVAC system faults rather than inter-individual differences in preferred temperatures. The analysis also shows that the "neutral" temperature in summer is greater than in winter, and the difference between summer and winter "neutral" temperatures is smaller than the difference between the midpoints of the summer and winter ASHRAE comfort zones. On average, women complain that it is cold at a higher temperature than men, and the temperature at which men complain that it is hot is more variable than for women. Analysis of response times and actions provides information that may be useful for designing a dispatching policy, and it also demonstrates that there is potential to reduce the labor cost of HVAC maintenance by 20% by reducing the frequency of thermal sensation complaints.

INTRODUCTION

Responding to unsolicited complaints contributes to the operation and maintenance cost of buildings. However, there is little information available to assess the magnitude of this contribution. Since some complaints are related to environmental variables such as temperature, and since some environmental variables are controlled in most buildings, it should be possible to manage complaints and, consequently, the cost of complaints through proper operation of the building control systems. However, before an operational policy for managing unsolicited complaint costs can be developed, an understanding of how and why unsolicited complaints occur is needed. Too little is known yet about the relative frequency of different kinds of complaints, the conditions that result in unsolicited complaints, the root cause of unsolicited complaints, and the time required to diagnose complaints.

Information about unsolicited complaints in buildings appears to be completely lacking in the open literature. This author has been unable to find a single article published in the open literature that describes, documents, or analyzes unsolicited complaint data in buildings. However, the frequency of various symptoms and levels of satisfaction with the indoor environment have been recorded in numerous field studies (e.g., Zweers et al. 1992, Hodgson et al. 1991). Health symptoms reported on surveys are often interpreted as complaints. Since these "complaints" are solicited, neither the relative frequencies nor the absolute frequencies of these symptoms will necessarily reflect the corresponding frequencies of unsolicited complaints.

There is a large body of information on how people perceive and react to the indoor environment based on laboratory studies and on field studies involving surveys or questionnaires. For thermal and olfactory sensations, relations between physical variables and perceptions have been studied in detail (Fang et al. 1996; Fanger et al. 1988, 1985; Fanger 1982; McIntyre 1980; Olesen et al. 1978; Olesen 1977). These relations are often formulated as mathematical relations involving the predicted percentage dissatisfied. Mathematical relations of this type are typically based on semi-empirical correlations derived from laboratory tests. While occupants may be assumed to be dissatisfied if they complain, the converse is not necessarily true. Therefore, models of percent dissatisfied will not necessarily predict unsolicited complaint behavior.

The causes of health symptoms and poor ratings of environmental conditions have been investigated with three differ-

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ent methods. The first is the use of laboratory experiments described above. The second method is the epidemiological approach, which involves assessing the intensity and frequency of symptoms with a survey and then deducing cause based on correlations, often between survey data and physical measurements. For example, Brill et al. (1984) used data from surveys to conclude that thermal comfort "complaints" were correlated with body size. Smaller occupants, who were more often women, were found to complain more about conditions being too cool and about temperature fluctuations. It was concluded that "purely environmental solutions to thermal comfort are probably unattainable, given that body type tends to alter responses so strongly." Hodgson et al. (1991) used a questionnaire and environmental measurements to demonstrate that mucous membrane irritation and central nervous system symptoms are related to concentrations of volatile organic compounds (VOCs), crowding, clothing insulation, and lighting intensity. A third method of investigating causation is with intervention studies. This method avoids some of the pitfalls associated with the use of surveys or questionnaires in the epidemiological approach because there is a control group. Intervention has been used by Jaakkola et al. (1991) to show that reduced ventilation rates slightly increased the frequency of sick building syndrome (SBS) symptoms. Wyon (1992) used intervention to study the relation between SBS symptoms and nine technical intervention measures.

There is very little information in the open literature indicating how much time it does or should take to diagnose and resolve individual complaints. Dohrman and Alereza (1986) give general formulas for predicting overall maintenance costs. No information regarding individual maintenance tasks is provided.

This paper contains the first statistical analysis of unsolicited complaints. The analysis is based on data recorded in two computerized complaint logs. Collectively, these logs contain thousands of unsolicited complaints from hundreds of buildings, tens of thousands of occupants, and tens of millions of square feet of building space. This analysis leads to a new understanding of unsolicited complaints and provides answers regarding questions about absolute and relative frequencies of complaints, conditions that cause the most common complaints, the cause of these conditions, and the amount of time required to resolve the most common complaints.

FACILITIES AND COMPLAINT LOGS

The two complaint logs correspond to two large collections of buildings. In all buildings in these two sets there is a formal procedure for occupants to complain about a problem. They call a telephone number that is answered by a dispatcher who records the complaint in a computerized database and initiates the resolution of the complaint. The two logs will be referred to as Log A and Log B.

Log A is from a facility near the gulf coast of Texas consisting of 115 structures totaling approximately 3 million square feet. The structures include a wide range of building types from semi-permanent trailers to large commercial office buildings. The structures are used for many different functions including weather monitoring and laboratory work, in addition to typical office work. Approximately 7,500 persons work in buildings corresponding to Log A.

Log B is from a large set of facilities distributed throughout the midwestern United States. The total number of buildings corresponding to Log B is 575. Of these, 482 are central office buildings, and the remainder are administrative buildings or data centers. The total number of square feet is approximately 17.2 million, and the total number of persons working in these buildings is approximately 16,000.

Log A and Log B contain the entries noted in Table 1. In Log A there are six complaint codes corresponding to the following environmental complaints: hot, cold, too much air, not enough air, high humidity, and low humidity. Air quality complaints were not recorded. The stated temperature is the temperature in the space where the complaint occurred at the time that the complaint occurred. In most cases, it is read by the occupant from a thermometer on the thermostat. In other cases, a parameter other than space temperature (e.g., supply duct temperature) was recorded instead of the space temperature, but it was often difficult to ascertain when this was done because there was no indication that it was not space temper-

TABLE 1
Entries in Log A and Log B

Entry	Log A	Log B
Date of complaint	X	X
Call-in time	X	X
Name of caller	X	X
Phone number of caller	X	
Building where problem exists	X	X
Equipment or location of problem	X	X
Complaint code	X	X
Stated temperature	X	
Operator action code 1	X	
Operator action code 2	X	
Dispatch time	X	
Feedback time	X	
Field action code 1	X	
Field action code 2	X	
Resultant temperature	X	
Remarks on problem, diagnosis, or work performed	X	X
Indication of whether the record was carried over to another day or was the completion of a call from a previous day	X	

ature. The feedback time is the time at which the field technician calls back to report that either the problem has been diagnosed and solved or that the problem has been diagnosed and is significant enough to warrant generating a work order to solve it. In many cases, especially when the number of complaints on a particular day is unusually high, the field technicians do not call back after resolving each complaint. Instead, they may resolve several complaints and then call back regarding all of those complaints at the same time. The resultant temperature is the temperature recorded at the location of the complaint after the complaint was resolved (i.e., at about the feedback time). As with the stated temperatures, this was not always space temperature, and no indication was provided if it was not the space temperature. Complaints entered in Log A during the twelve-month period beginning September 1, 1995, and ending August 31, 1996, were analyzed.

There are 36 complaint codes in Log B. Most are for maintenance complaints such as "broken," "clogged," "leaking," etc. The environmental complaints recorded in Log B are: drafty, noisy, too hot, too cold, high humidity, and low humidity. There was no code for air quality complaints. The comments entry was searched for instances of the words *odor*, *smell*, *dusty* (air), and *air quality*. Complaints entered in Log B during the period beginning January 1, 1997, and ending April 23, 1997, were analyzed.

STATISTICAL METHODS

In addition to calculating descriptive statistics, hypothesis tests were conducted on several of the variables in or derived from Log A. Four kinds of statistical tests are reported. They are tests of location (e.g., is the mean or median of X the same as Y), tests of scale (e.g., is the standard deviation of X the same as Y), tests of association (correlation), and tests of goodness-of-fit. In all cases, nonparametric tests were used because they are generally more robust and because the sample sizes were so large that the power was high even though the tests are less efficient. In all of the tests, the sample sizes were sufficiently large to assume that the sampling distributions of the statistics were the asymptotic sampling distributions. Unless otherwise noted, the methods used in this paper are described in detail in Siegel and Castellan (1988).

For the location tests, the robust rank order statistic, U, was used. This statistic and the corresponding test are an alternative to the Wilcoxon-Mann-Whitney rank-sum statistic, W, and the test corresponding to W. The advantage of using U instead of W is that it is applicable to the Behrens-Fisher problem of testing location when the scale of the two populations differs, whereas the Wilcoxon-Mann-Whitney rank-sum test is not (Lehmann 1975). The sampling distribution of U is asymptotically standard normal, so U is interpreted in the same way as a standard normal deviate.

For scale tests, the Moses rank-like statistic was used. The sampling distribution of the Moses rank-like statistic is asymptotically normal, so the statistic is standardized, and the corresponding standard normal deviate associated with this statistic, denoted as Z_M, is reported.

For tests of association, the Spearman rank-order correlation coefficient, *R*, and the Kendall τ coefficient were used. The sampling distributions of these statistics are asymptotically normal, so the statistics are standardized, and the corresponding standard normal deviates associated with the statistics, denoted as Z_R and Z_τ, are reported.

The χ^2 test and the Kolmogorov-Smirnov test were used to test for goodness-of-fit.

Robust location (e.g., mean) and scale (e.g., standard deviation) estimators were used to analyze properties of the tails of some distributions because the data are known to be corrupted with manual entry errors. The estimates are determined by first eliminating outliers. Outliers are defined as those values that are more than three times a robust scale estimate from a robust location estimate. The final values of the robust location and scale estimates are computed as the sample mean and standard deviation of the population after the outliers have been removed. This method is called reweighted least squares (RWLS) and is described by Rousseeuw and Leroy (1987).

In addition to the test statistics, the probability associated with the test is reported. Single-sided tests are denoted by the subscript "s" on the p-value, and double-sided tests are denoted by the subscript "d."

The tests on location and scale parameters described above are based on the assumption that the samples are independent. The independence assumption may be violated in this data set because the log contains entries that have the same location, or the same caller, or because many of the complaints were handled by the same technician. Correlation caused by multiple entries from the same complainer is not likely to be a significant problem because the "between-subjects" standard deviation in making subjective ratings of thermal sensation is comparable with the "within-subjects" standard deviation in making subjective ratings of thermal sensation (McIntyre 1980). In other words, there is as much variation from thermal sensation ratings taken many times from a single individual under fixed conditions as there is from a large population of individuals rating the same conditions just once. The results are presented with the assumption that the independence assumption is valid or at least that violation of this assumption does not have a significant impact on the results. However, the possibility that correlation could affect the reported results should not be forgotten.

STATISTICAL ANALYSIS

In this section, analysis of complaint frequencies, temperatures at which thermal sensation complaints occurred, and response times are described. Log A only contains information about thermal sensation, humidity, and air motion complaints, so Log B is used for the complaint frequency analysis. Log A is used for the temperature and time analysis.

Complaint Frequency

There were 2405 complaint entries in Log A. The frequency of these complaints was: too hot (1373), too cold (950), too much air (30), not enough air (19), high humidity (19), and low humidity (8). The sum of the number in each of the six categories does not add up to the total number of complaints because the code for some complaints was missing or out of range. The statistics show that 97% of the complaints in Log A are "too hot" or "too cold."

There were 11,521 complaint entries in Log B. Of these, 2123 could be classified as environmental complaints. The frequency of the environmental complaints is as follows: drafty (15), noisy (69), too cold (1001), too hot (621), too humid (12), too dry (85), odor (60), smell (253), dusty air (3), and air quality (1). If "hot" and "cold" complaints are considered as a single category called "thermal sensation," then the three most frequent categories in the log are: repair (1823), examine (1663), and thermal sensation (1622). Since the repair and examine categories apply to many different kinds of complaints, the data indicate that thermal sensation complaints are the single most common kind of complaint, occurring even more often than any single kind of maintenance complaint such as burned out light bulbs, clogged toilets, or plumbing leaks. Figure 1 shows the absolute and relative frequencies of environmental complaints recorded in Log B. *Smell*, *odor*, *dusty air*, and *air quality* have been classified as IAQ, and complaints of high and low humidity have been classified simply as *humidity*. In comparison to other environmental complaints, thermal sensation complaints are the overwhelming majority (77%). This finding is consistent with BOMA (1988) and conflicts with Olesen and Madsen (1986), who state that "the most common complaint in air-conditioned spaces for sedentary work is draught."

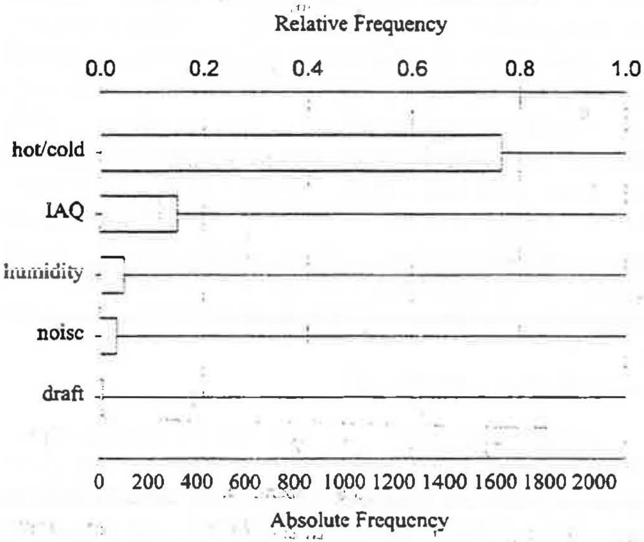

Figure 1 *Absolute and relative frequencies of environmental complaints in Log B.*

Analysis of Stated Temperatures for Thermal Sensation Complaints

The temperature exposure levels at facility A are determined by the temperature distribution. Direct measurement of the temperature distribution at facility A was not possible, but some information about it may be derived from data in the complaint log. This is possible because stated and resultant temperatures were recorded for the humidity and air motion complaints. The hypothesis is that the mean building temperature is equal to the mean value of the stated and resultant temperature distributions for the humidity and air motion complaints. In other words, conditions causing humidity and air motion complaints do not cause a shift in the mean value. Figure 2 shows the stated temperature distribution for humidity and air motion complaints. Figure 3 shows the resultant temperature distribution for humidity and air motion complaints.

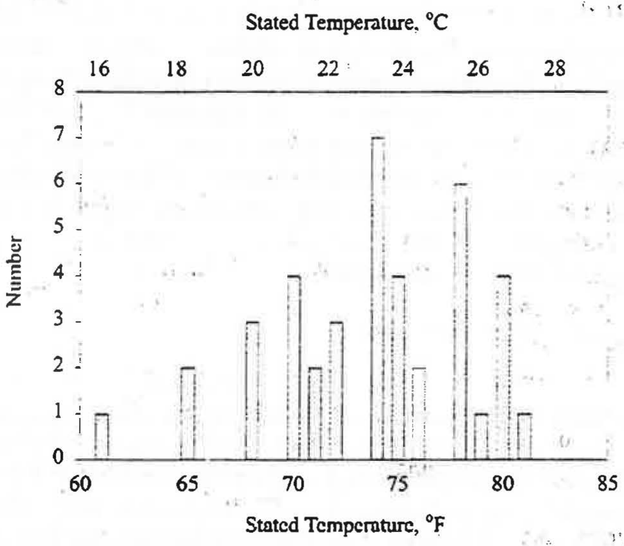

Figure 2 *Stated temperature distribution of the humidity and air motion complaints.*

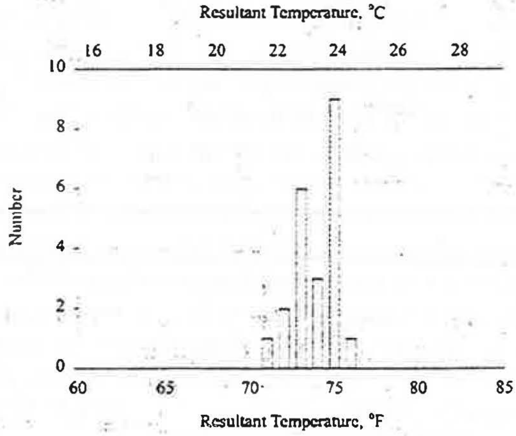

Figure 3 *Outlier-free resultant temperature distribution of the humidity and air motion complaints.*

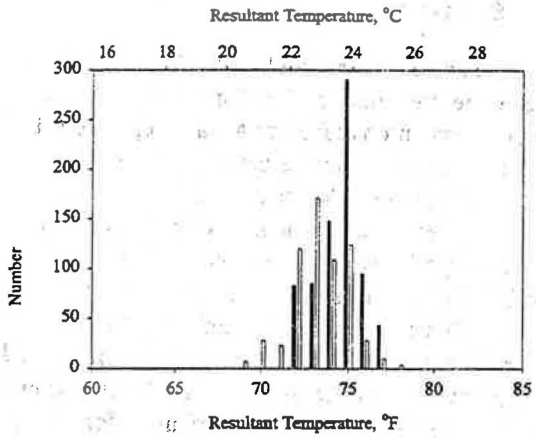

Figure 4 *Distributions of outlier-free resultant temperatures for hot and cold complaints. Hollow bars are cold complaints. Solid bars are hot complaints.*

complaints after outliers and complaints associated with a serious fault condition were eliminated. Figure 4 shows the resultant temperature distribution for hot and cold complaints after outliers and complaints associated with a serious fault condition were eliminated. Table 2 and Table 3 show the descriptive and tests statistics for these populations. The hypothesis is supported by the fact that the p-value for the location test on the outlier-free stated and resultant temperatures of the humidity and air motion complaints is high. It is also supported by the fact that the average of the mean values of the outlier-free hot and cold resultant temperatures equals the mean value of the outlier-free humidity and air motion resultant temperatures. Therefore, it is assumed that the mean building temperature was 73.9°F (23.3°C).

TABLE 2
Statistics of the Outlier-Free Stated and Resultant Temperature Distributions for Humidity and Air Motion Complaints

	Stated	Resultant	Test Statistic	p_d
Sample mean	73.8°F (23.2°C)	73.9°F (23.3°C)	U = –0.21	0.83
Sample standard deviation	4.7°F (2.6°C)	1.3°F (0.7°C)		

TABLE 3
Statistics of the Resultant Temperature Distributions for Hot and Cold Complaints

	Hot	Cold
Sample mean	74.5°F (23.6°C)	73.4°F (23.0°C)
Standard deviation	1.3°F (0.7°C)	1.6°F (0.9°C)

The standard deviation of the outlier-free resultant temperatures is a lower bound on the standard deviation of the building temperature distribution because these points were all just checked and adjusted by a technician. The standard deviation of the outlier-free stated temperatures for the humidity and air motion complaints is probably an upper bound on the standard deviation of the building temperature distribution because of the fact that there was a reported problem at all of these locations. The Kolmogorov-Smirnov test was used to test the hypothesis that the outlier-free distributions are normal. All four tests showed a statistically significant difference from a normal population. This may be due in part to "recruitment" errors (i.e., the tendency for people reading a visual scale such as a thermometer to favor certain familiar values or prominent markings). Also, there is visual evidence of skew in the stated temperature distribution of the humidity and air motion complaints.

Figure 5 shows the frequency distribution of the hot and cold stated temperatures. The solid bars are the hot complaints and the hollow bars are the cold complaints. Conclusions to be drawn from the stated temperature distributions are based on the assumption that the stated temperatures, which are reported by the occupants, are not exaggerated. The fact that the mean values for each population are reasonable adds credibility to this assumption. However, it would be helpful to determine whether or not there is bias in these readings. This could be accomplished with a direct digital control (DDC) system by recording the stated temperatures and the temperature indicated by the DDC system, simultaneously. Note that having low complaint frequencies at high and low temperatures does not imply that complaints will not occur at those temperatures. It means that exposure to those temperatures was infrequent.

An important feature of Figure 5 is that the hot and cold stated temperature distributions overlap very little. If the

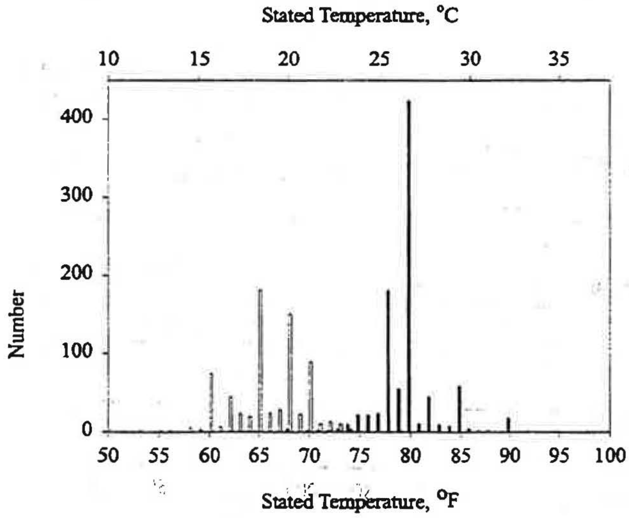

Figure 5 *Distributions of hot and cold stated temperatures. Hollow bars are cold complaints. Solid bars are hot complaints.*

building temperatures had been held between 70°F and 75°F at all times, then approximately 96.5% of the complaints would not have occurred. In other words, few of the complaints can be reasonably attributed to inter-individual differences in preferred temperature. Most are the result of poor control performance and faults and, therefore, represent potential cost savings.

Table 4 summarizes the descriptive and test statistics of the hot and cold stated temperature distributions. Although it is obvious from Figure 5 that the location of the populations differs, the difference was tested and shown to be strongly statistically significant. The fact that the sample standard deviation of the cold complaint population is greater than that of the hot complaint population is also statistically significant. One possible explanation for this difference is that coping behaviors have a stronger effect when it is cold than when it is hot. For example, larger adjustments in clothing insulation and metabolic rate are available for dealing with cold conditions than with hot conditions. Another possible explanation is that the building temperature distribution may not be symmetrical.

TABLE 4
Statistics of the Stated Temperature Distributions for Hot and Cold Complaints

	Hot	Cold	Test Statistic	p_s
Sample mean	79.9°F (26.6°C)	65.7°F (18.7°C)	U = 575.7	≅0
Sample standard deviation	3.1°F (1.7°C)	3.7°F (2.1°C)	$Z_M = 4.23$	1.17×10^{-5}

According to Gagge et al. (1971), the onset of sweating in clothed, sedentary subjects is 75°F (24°C). This implies that 95% of the people who complained that it was too hot were sweating.

The PMV index is a prediction of the average thermal sensation rating of a large population as a function of a set of six variables that affect thermal sensation at steady state, including air temperature (Fanger 1982). The ISO standard for thermal comfort states that PMV should not exceed 0.5 (ISO 1984). Assuming that the metabolic rate of the occupants is 1.2 met, the clothing insulation is 0.6 clo, the mean air velocity in the occupied space is 30 fpm, the relative humidity is 50%, and the mean radiant temperature is equal to the air temperature, the value of PMV reaches the level of 0.5 when the air temperature is 79.2°F. The upper limit of the ASHRAE comfort chart for summer is 79°F at 50% relative humidity, but it extends up to 81°F at a relative humidity of just under 20% (ASHRAE 1992). Log A indicates that just 36% of the complaints occur at stated temperatures of 79°F and lower but that this value increases to 82% when the threshold is raised just one degree to 80°F (note that these are not percent dissatisfied, but rather the percent of the total complaints recorded).

Current comfort standards are based on acceptable levels of dissatisfied, where the percent dissatisfied has been chosen somewhat arbitrarily as a particular value of an index such as PMV. Since there is a growing interest in using comfort standards as operating standards, it seems reasonable that the standards should be based on operating data. The data in Log A show a dramatic increase in the number of complaints from 79°F to 80°F. This increase may either be real or an artifact of recruitment errors since the data were recorded manually. If it is real, it may be due to a psychological trigger effect, or it may be a physiological effect. If it is a psychological trigger effect and if the purpose of the standard is to specify operating conditions under which complaint rates are low, then the standard should stipulate that the temperature remain below 80°F, regardless of the values of other hygrothermal parameters, such as humidity or clothing insulation value, in order to avoid the trigger and its associated cost. Automated recording of stated temperatures (e.g., with a DDC system) could be used to determine whether or not the large increase is real.

Gender differences were also tested. The gender of the caller was determined from the name in the log. Of the 2323 hot and cold complaints, the gender of the caller could be determined in 1901 cases. Of these 1901, 963 were female and 938 were male. The proportion of males and females in the population is unknown. Table 5 summarizes the descriptive and test statistics and the results of the tests on location and

TABLE 5
Statistics Regarding Gender Differences

Complaint	Descriptive Statistic	Female	Male	Test Statistic	p_s
Hot	Mean	79.8°F (26.6°C)	79.9°F (26.6°C)	U = 0.36	0.39
Hot	Standard deviation	2.8°F (1.6°C)	3.5°F (1.9°C)	$Z_M = 2.72$	0.0033
Cold	Mean	66.3°F (19.1°C)	65.5°F (18.6°C)	U = 3.0	0.0013
Cold	Standard deviation	3.5°F (1.9°C)	3.7°F (2.1°C)	$Z_M = 1.15$	0.125

TABLE 6
Statistics Regarding Seasonal Differences

Complaint	Descriptive Statistic	Summer	Winter	Test Statistic	p_s
Hot	Mean	80.0°F (26.7°C)	80.4°F (26.9°C)	U = 1.55	0.061
Hot	Standard deviation	3.1°F (1.7°C)	3.6°F (2.0°C)	$Z_M = -2.57$	0.995
Cold	Mean	66.4°F (19.1°C)	64.9°F (18.3°C)	U = 4.7	1.3×10^{-6}
Cold	Standard deviation	4.0°F (2.2°C)	3.2°F (1.8°C)	$Z_M = 2.89$	0.0019

scale. On average, men and women complain that it is too hot at the same temperature, but there is more variability in the temperature at which men complain that it is too hot. On average, women complain that it is cold at a higher temperature than men, but the variability in the temperature at which they complain that it is cold is approximately the same. These results are almost certainly confounded by women complaining for men, and vice versa. However, the fact that two of the differences are statistically significant indicates that there are certainly gender differences because removal of the confounding data could only make the apparent differences larger.

Statistical differences between thermal sensation complaints in summer and winter were investigated. Summer was considered to be June, July, and August, while winter was considered to be December, January, and February. Table 6 shows the descriptive and test statistics regarding seasonal differences. On average, occupants complain that it is too hot at approximately the same temperature in both summer and winter. The p-value for the scale test of the hot complaints is nearly one because the test statistic indicates that the summer standard deviation is larger than the winter standard deviation. This is likely due to the presence of outliers. The RWLS estimates of the location parameters for the summer and winter hot populations were 79.6°F and 79.4°F, respectively. The RWLS estimates of the scale parameters for summer and winter were 1.12°F and 1.87°F, respectively. Based on the "outlier-free" data from the RWLS algorithm, the location difference (now with the opposite sign) is still not statistically significant (U = 0.69, $p_s = 0.25$), but the scale difference is ($Z_M = 4.35$, $p_s = 6.8 \times 10^{-6}$). On average, occupants complain that it is too cold at a higher temperature in the summer than in the winter. In the summer, there is also more variability in the temperature at which they complain that it is cold than in the winter.

Neutral temperatures were estimated for each gender in summer and winter. The neutral temperature is defined as the temperature at which the density function of the stated temperatures for hot complaints equals the density function of the stated temperatures for cold complaints. This definition is shown in Figure 6. The density functions were evaluated based on the robust location and scale estimates described in "Statistical Methods," assuming that the density functions were normal.

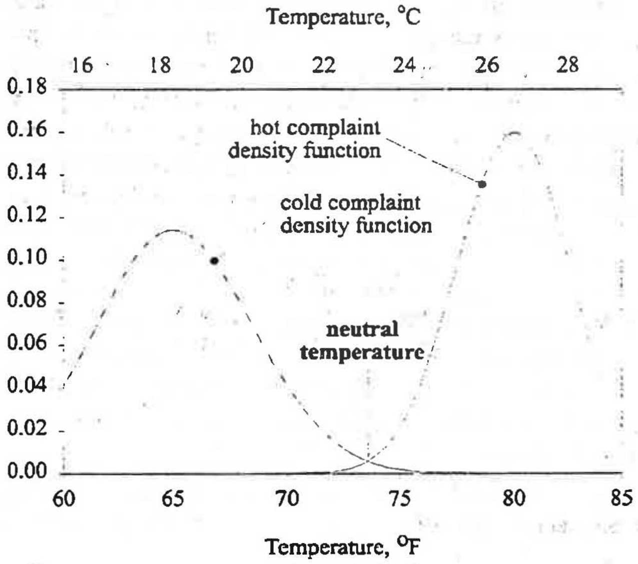

Figure 6 *Definition of neutral temperature.*

Table 7 shows the neutral temperatures for each of the four cases. The neutral temperatures are higher in summer than in winter. All of these values fall within the ASHRAE comfort zone (ASHRAE 1992). However, these results indicate that the difference between summer and winter neutral temperatures is smaller than what is indicated by the ASHRAE comfort zone. The midpoint of the ASHRAE comfort zone for summer is 5°F greater than the midpoint for winter. The difference, according to the analysis of the stated temperatures, is only 0.7°F for women and only 2.0°F for men.

TABLE 7
Neutral Temperatures

	Summer	Winter
Male	75.6°F (24.2°C)	73.6°F (23.1°C)
Female	75.8°F (24.3°C)	75.1°F (23.9°C)

These differences may be small because the facility was located in an area where the winter weather is relatively mild and the summer weather is extremely hot and humid, so clothing insulation values may not be much higher in the winter than in the summer.

Analysis of Time Information

The complaint log contains three time variables: the call-in time, the dispatch time, and the feedback time. From these three time variables, three time intervals can be calculated directly. The first is the time required to take, record, and dispatch the call. This time interval will be referred to as the "central dispatch time," and it will be denoted as t_{cd}. The central dispatch time is calculated by subtracting the call-in time from the dispatch time. The second time interval that can be calculated directly is the time required by the field technician to respond to the dispatch message, travel to the complaint location, diagnose the problem, and (when possible) solve the problem. This time interval will be referred to as the "transit and diagnosis time," and it will be denoted as t_{td}. The transit and diagnosis time is calculated by subtracting the dispatch time from the feedback time. The third time interval that can be calculated directly is the total time required to resolve a complaint. This time interval will be referred to as the "total resolution time," and it will be denoted as t_{tr}. The total resolution time is calculated by subtracting the call-in time from the feedback time. The definitions of these time intervals are depicted in Figure 7.

Table 8 shows the sample mean and median of the three time intervals for the hot and cold complaint populations.

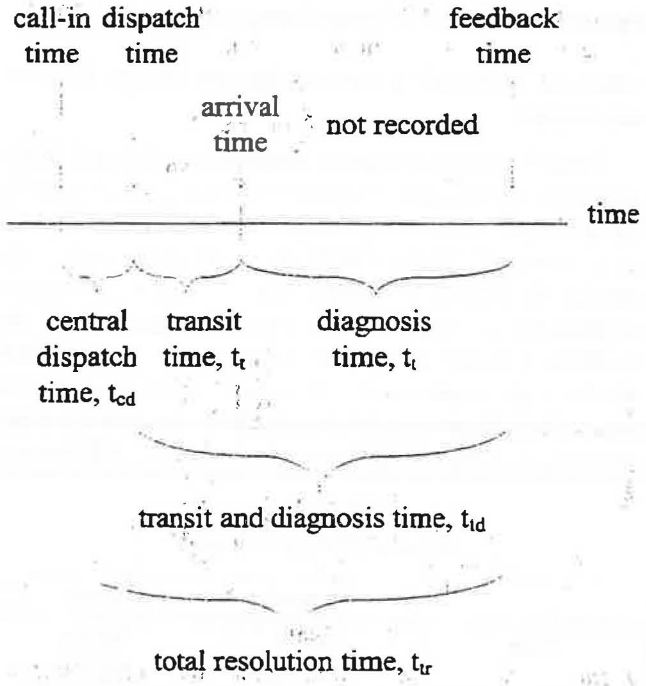

Figure 7 Time line showing definitions of time intervals related to a complaint.

TABLE 8
Sample Mean and Median Values Of t_{cd}, t_{td}, and t_{tr} For Hot and Cold Complaints in Hours

	Hot		Cold	
	Mean	Median	Mean	Median
t_{cd}	0.17	0.083	0.27	0.083
t_{td}	1.6	1.0	2.0	1.5
t_{tr}	1.6	1.0	2.1	1.5

Different samples were used to calculate these statistics because of missing data and data entry errors in the complaint log. One pattern that emerges from these statistics is that the mean values are consistently larger than the medians, indicating that the distributions are skewed to the left. Another consistent pattern that emerges is that the location parameters for cold complaints are larger than for hot complaints. These differences are statistically significant. For the central dispatch time, $U = 3.29$ and $p_s = 4.96 \times 10^{-4}$. For the transit and diagnosis time, $U = 5.16$ and $p_s \cong 0$. The difference was attributed to the fact that hot complaints sometimes have priority over cold complaints because hot conditions are more likely to cause damage to equipment such as computers.

Since the time at which the field technician arrives at the complaint location is not recorded, the transit time cannot be separated from the diagnosis time on a sample-by-sample basis. However, the mean and standard deviation of the transit time and the mean and standard deviation of the diagnosis time can be estimated based on a probabilistic model of the transit and diagnosis process. This was done with a simple model based on two assumptions. The first is that t_t is independent of t_d. The second is that t_t and t_d are exponentially distributed. The mean values (and standard deviations) of t_t and t_d were estimated by fitting the theoretical density function to the observed frequency distribution by minimizing the χ^2 norm. The observations were collected into 13 bins with 15-minute intervals for the first two hours, 30-minute intervals for the next two hours, and a single interval for the remaining time. This leads to a χ^2 test with 12 degrees of freedom. Table 9 shows the parameter estimates.

The χ^2 test was used to test the goodness-of-fit for each population. For the hot complaints, the residuals are statistically significant ($\chi^2 = 40.25$, $p = 0.000066$), but for the cold complaints they are not ($\chi^2 = 15.24$, $p = 0.22$). Figure 8 and Figure 9 show the observed and estimated frequency distribu-

TABLE 9
Estimated Mean Transit Time and Mean Diagnosis Time for Hot and Cold Complaints (in Hours)

	Hot	Cold
Mean transit time	0.12	0.25
Mean diagnosis time	1.4	1.7

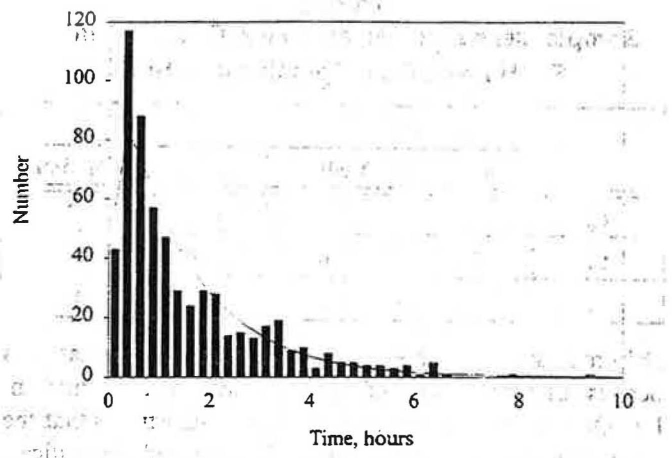

Figure 8 *Observed and estimated frequency distribution of transit and diagnosis times for hot complaints.*

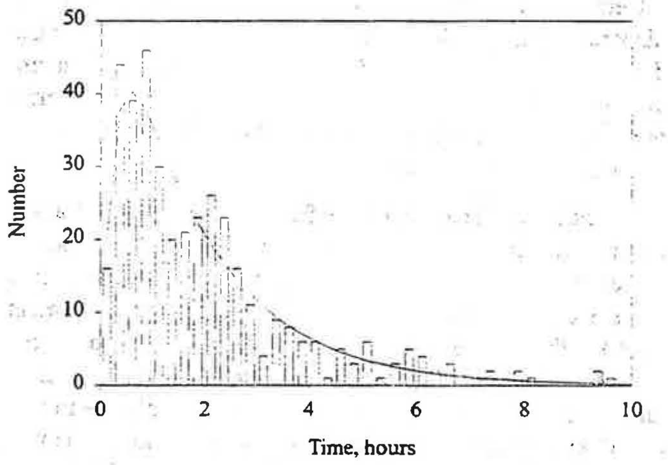

Figure 9 *Observed and estimated frequency distribution of transit and diagnosis times for cold complaints.*

tions for the hot and cold complaints, respectively. Although they appear qualitatively the same, the model is unable to satisfactorily estimate the magnitude of the peak of the hot distribution. The residual in that one bin is 30% of the χ^2 statistic.

The fact that the transit and diagnosis time may be modeled as a sequence of two independent exponential distributions (at least for the cold complaints) has certain implications for dispatching policies. Exponential distributions are memoryless. Mathematically, this means that the conditional distribution is unaltered by the current value. Practically speaking, this means that no information about how much longer one must wait for a technician to arrive at the complaint location is gained by knowing how long one has already waited, and no information about how much longer a technician must be at the complaint location is gained by knowing how long the technician has already been there. This means that decisions about dispatching should not be based solely on these waiting times. Instead, information about where the technician is and what the technician has learned should be used to estimate the remaining transit time and diagnosis time, respectively.

Time-Temperature Correlation Analysis

Correlation between response times and stated temperatures was investigated because of the difference in the response times to hot and cold complaints. Figure 10 shows a scatter plot of the total resolution time vs. stated temperature for hot and cold complaints. From the figure, it is clear that within each population there is little correlation between the total resolution time and the stated temperature. Both the Spearman rank correlation coefficient and the Kendall τ coefficient were computed for every combination of the three time intervals and two complaint types. Of the 24 coefficients computed, 18 were negative. All of the coefficients for t_{cd} were negative, and all of the τ coefficients were negative. However, none of the tests based on these coefficients was statistically significant. The standard normal deviate with the largest magnitude was $Z_\tau = -1.07$ for cold stated temperatures and central dispatch times.

The implication of this finding is that the "intensity" of a thermal sensation complaint, as measured by the stated temperature, cannot be used to predict the time required for a response. From the point of view of the occupant, it means that one should not expect a faster response to a complaint when it is intensely hot than to a complaint when it is just moderately hot, nor to a complaint when it is intensely cold than to a complaint when it is just moderately cold.

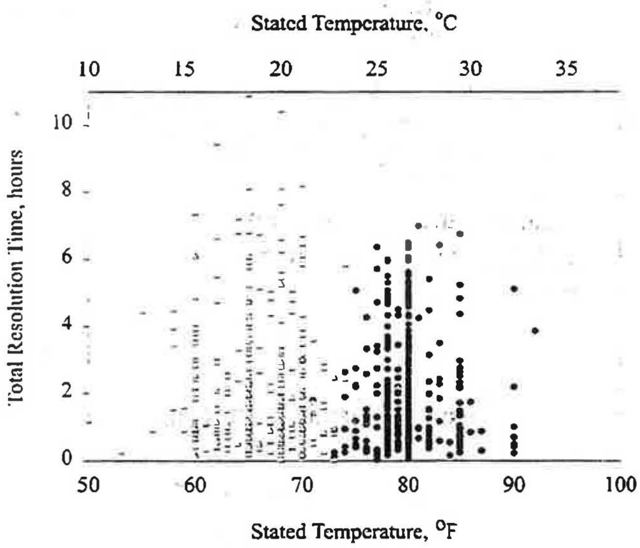

Figure 10 *Scatter plot of total resolution time vs. stated temperature. Solid circles are hot complaints. Hollow triangles are cold complaints.*

Analysis of Operator Actions and Field Actions

In this section, an analysis of operator and field actions recorded in the complaint log is described. Figure 11 shows a frequency diagram of the operator actions performed, and Figure 12 shows a frequency diagram of the field actions performed. Many of the operator actions involve adjusting setpoints, starting equipment, or stopping equipment. Many of these actions could be automated with a modern DDC system if it were properly programmed. Many of the field actions also involve adjusting setpoints, starting equipment, or stopping equipment. These actions are performed in the field because of the absence of a networked DDC system. Most of the controls are pneumatic. With a modern DDC system, these actions could be performed remotely, and like the operator actions of this type, they could also be automated.

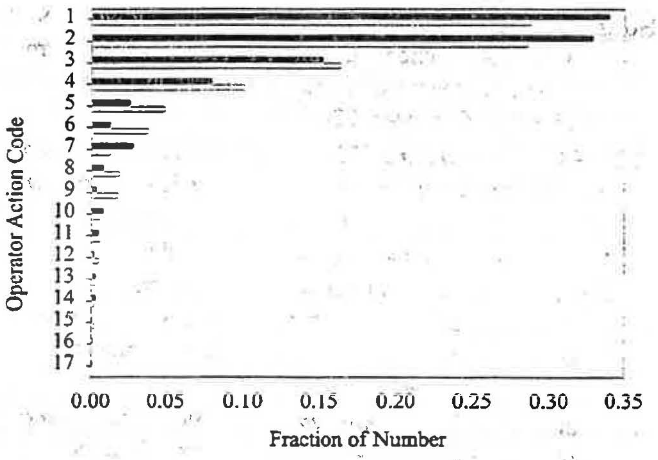

Figure 11 Frequency distribution of operator actions. Solid bars are hot complaints. Hollow bars are cold complaints. Codes are described in Table 10.

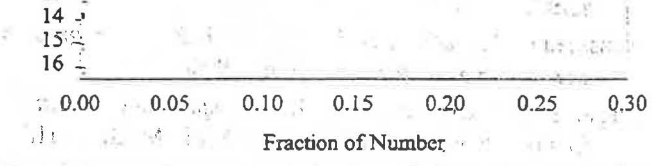

Figure 12 Frequency distribution of field actions. Solid bars are hot complaints. Hollow bars are cold complaints. Codes are described in Table 10.

TABLE 10
Operator and Field Action Codes

Code	Operator Action	Field Action
1	OK on CRT	No action
2	No control from DAC	Adjust thermostat
3	Adjust cold deck temp.	Turn over to work crew
4	No action	No entry in log
5	Adjust discharge air temp.	Center/reset cold deck
6	Adjust hot deck temp.	Adjust discharge air temp.
7	Change unit status	Minor repair
8	Change chilled water pump status	Change status
9	Change hot water pump status	Center/reset hot deck
10	No entry in log	Calibrate and set thermostat
11	Point inactive	Change hot water pump status
12	Unit inoperable	Adjust airflow
13	Computer off-line	Center/reset static pressure
14	Adjust static pressure	Turned over to engineering
15	Adjust hot water converter	Change chilled water pump status
16	Set-point pump on/off	Center/reset hot water converter
17	Rtu off-line	

In order to estimate the potential for reducing the complaint rate by upgrading the control system to a modern DDC system, assume that all setpoint adjustments could have been automated, that all start-stop operations could have been automated, and that the thermostat adjustments would not have been necessary. Furthermore, assume that the complaint would not have occurred if these tasks had been automated. In other words, assume that all complaints could have been eliminated except those that lead to the generation of a work order (field action "turned over to work crew"), those that required minor work but not a work order, those that required airflow adjustment, and those that were turned over to engineering. Also, assume that none of the complaints with stated temperatures of 71°F, 72°F, 73°F, or 74°F could be avoided. Under these assumptions, the total number of hot and cold complaints could have been reduced from 2323 to 679, which is a 71% reduction. The total time spent fielding complaints would have been reduced by 2980 hours in the 12-month period studied. If the labor cost is $35/h, then the cost reduction potential is $104,300/yr. This is a labor cost reduction potential. In Dohrman and Alereza (1986), it is shown that the median and mean cost of labor for HVAC maintenance in 1983 for commercial buildings was $0.15 per square foot and $0.184 per square foot, respectively. Based on the median value and a 4% increase per year, the labor cost for HVAC maintenance for facility A is $450,000 per year. The maintenance cost based on the mean and a 4% increase per year is $552,000 per year. These estimates imply that the potential for reducing thermal sensation complaints represents a potential reduction in the labor cost of HVAC maintenance of approximately 20%.

CONCLUSIONS

The following conclusions can be drawn from the analysis in this paper:

1. Thermal sensation complaints (hot and cold) are the single most common kind of unsolicited complaint in buildings and the overwhelming majority of unsolicited environmental complaints (77%).
2. Hot and cold complaints are rarely due to inter-individual differences in preferred temperature. They are usually due to HVAC faults or poor control performance.
3. Statistically significant differences exist in the temperatures at which men and women complain that it is hot and cold. There is more variability in the temperature at which men complain that it is hot than there is for women. On average, women complain that it is cold at a higher temperature than men.
4. The difference between summer and winter neutral temperatures is 2.0°F (1.1°C) for men and 0.7°F (0.4°C) for women. The neutral temperatures for both are higher in the summer.
5. There is no correlation between response time and complaint intensity for thermal sensation complaints.
6. Once on site, it takes 1.4 hours on average to diagnose a hot complaint and 1.7 hours on average to diagnose a cold complaint.
7. Most actions for thermal sensation complaints (71%) involve adjusting a control system setting.
8. There is a potential for reducing the labor cost associated with HVAC maintenance by 20% by reducing the frequency of hot and cold complaints.

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