A Survey Technique for Evaluating Heating, Ventilating, and Air-Conditioning Systems

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ABSTRACT

This paper presents a survey technique for rating HVAC systems. System components are grouped into categories. The components inside the categories are numerically rated from 1.0 to 5.0 in terms of mechanical system maintenance, service performance, and operation efficiency of the mechanical equipment. The component scores are averaged for each category. These scores are then averaged to give a single score for the whole system. To evaluate the consistency of survey ratings, a trial was conducted whereby on the same day, ten independent assessors with different years of job experience examined a range of equipment from two major HVAC systems (N = 200). A Cronbach's Alpha Internal Consistency Analysis of the averaged ratings gave a result of 0.76, indicating good agreement between assessors. These data show that apart from being able to reduce large datasets into a concise summary, the survey technique is robust and internally consistent.

INTRODUCTION

High indoor relative humidity is recognized as contributing to known health effects due to the growth and spread of biological agents including dust mites, fungi, bacteria, and viruses (Baughman and Arens 1996). Inadequate humidity control can lead to increased illness and IAQ complaints in all buildings and can foster the growth of mold on building surfaces (Arundel et al. 1986; Downing and Bayer 1993). This can lead to a number of indoor air quality (IAQ) issues, resulting in poor occupant health and comfort and property damage. High humidity can arise from a number of sources, such as the building envelope being compromised either through design issues or poor work practices, and other moisture events such as plumbing leaks.

A major underlying factor for the occurrence of adverse health symptoms in the modern sealed building can be a poorly functioning or incorrectly designed heating, ventilating, and air-conditioning (HVAC) system (Cooley et al. 1998). Therefore, the correct diagnosis of malfunctioning HVAC systems is important, particularly with regard to protecting occupant health and property and to avoid costly litigation associated with poor IAQ and humidity control (Fischer 1996). One of the problems in describing malfunctioning systems is that there can be different systems in operation in a building, thereby making it difficult in terms of comparing their effectiveness. Further, large amounts of data are created, which can be difficult to manage and interpret concisely for the client.

This paper presents a new survey that was developed to create a systematic approach for the examination of HVAC systems and to reduce a large amount of HVAC system-related data into a manageable and straightforward summary. While the survey provides a methodical approach for evaluating HVAC systems, it is important to know what degree of variation might be expected between different assessors. Therefore, a trial was conducted whereby on the same day different assessors, who came from a variety of occupations and had different levels of experience, used the survey to assess a large range of HVAC equipment.

MATERIALS AND METHODS

Survey Design

The HVAC system is first broken down into categories. These are plant-level categories, such as chiller plant systems, hot water systems, and pump systems, and then delivery-level categories, such as air-handling units (AHU), rooftop units

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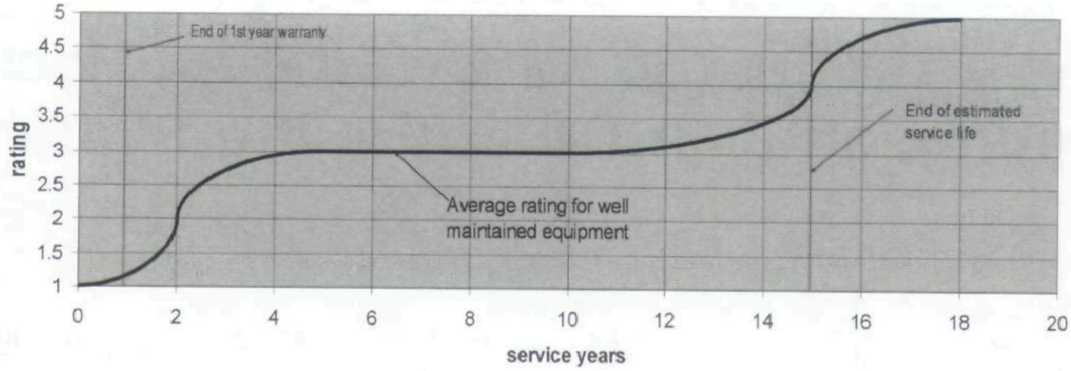

Figure 1 *Rating scores from an HVAC survey compared to the estimated service life of HVAC system components. The average rating of 3.0 represents the expected score for well-maintained equipment.*

Table 1. Typical Survey Table Showing Categories and Components with Ratings within the Categories

Air-Handling Unit	Rating
Condition of equipment	3.0
Fans, motors, service	3.5
Coils, filters, belts, gauges, alarms, service	3.3
Condensate systems, drains, pans, etc.	4.0
Outside air systems: dampers, operation, etc.	3.9
Heating systems: hot water, electric, gas	2.5
Heating systems: preheat, reheat, mixing, etc.	2.9
AVERAGE	3.3
Return Air Unit, Direct Expansion	
Compressors, charges, operation	3.0
Condition of equipment	3.5
Fans, motors, service	3.8
Coils, filters, belts, gauges, alarms,	3.1
Condensate systems, drains, pans, etc.	4.4
Outside air systems: dampers, operation, etc.	4.0
Heating systems: hot water, electric system	3.3
AVERAGE	3.6

(RTU), and direct expansion (DX) and fan coil units (FCU) (Katipamula et al. 2001). These categories then have components that are to be examined listed inside them. These include, but are not limited to, fans, motors, coils, filters, belts, gauges, alarms, condensate system drains and pans, outside air dampers, electrical wiring, compressors, etc. Table 1 shows a typical category table with accompanying scores.

Numerical scores on a scale from 1.0 to 5.0 are applied to the components. The scores are not limited to whole numbers (e.g., a score of 2.4 or 3.6 can be given). The assessor evaluates the equipment using these numbers in terms of mechanical system maintenance, service performance, and operation efficiency of the mechanical equipment with regard to energy management/building automation systems. Benchmark scores for ratings are as follows:

1. 1.0: New equipment or systems, in warranty, and/or correct intended operating condition.
2. 2.0: Exceptionally maintained for equipment of its age and is operating as intended and designed.
3. 3.0: Maintained, good condition, and fully functional for equipment age, operating as intended. Preventive maintenance is required to maintain present status.
4. 4.0: Neglected and/or not maintained. Repairs and substantial work are required by skilled technicians for the restoration of equipment to serve the intended purpose. Life-cycle costs should be considered to determine if repair or replacement is appropriate before committing substantial funds for restoration.
5. 5.0: Nonfunctional and needs replacement.

These scores were derived from the *ASHRAE Handbook—HVAC Applications* (ASHRAE 2003). Figure 1 shows the relationship of the scores to the service life of a component. Reliability of components as compared to equipment age influences the curve during the early and late years of the expected service life.

An overall rating called the HVAC Component Mean Evaluation (HVAC CME) is then generated from the compiled ratings. In this procedure the scores on each component are averaged to give a score for the HVAC system category. Category scores are then in turn averaged to give an overall mean score for that particular HVAC system. Different categories can be weighted to reflect their importance in the HVAC system. For example, a rating for a chiller system can be given more weight than a rating for a fan coil unit. This rating can be based on value, importance to operation of the HVAC system, and cost of replacement.

Table 2. Mean Ratings from an Investigation of the HVAC System of One School By Up to Ten Assessors Using a New Survey Rating System[*]

Categories	Assessor										Mean	SE	N
	1	2	3	4	5	6	7	8	9	10			
AHU # 10	3.4^{b}	3.7^{b}	3.1^{a}	3.3^{b}	2.7^{a}	3.8^{b}	4.1^{c}	3.5^{b}			3.4	0.15	8
AHU # 9	3.4^{a}	3.6^{b}	3.7^{b}	3.5^{a}	2.9^{a}	3.8^{b}	4.0^{b}	3.5^{a}			3.5	0.11	8
AHU # 1	3.2^{b}	3.2^{b}	2.9^{a}	2.9^{a}		3.7^{b}	3.1^{a}	2.9^{a}	3.0^{a}	2.6^{a}	3.0	0.10	9
AHU # 2	3.2^{b}	3.3^{b}	2.9^{b}	3.0^{b}		3.6^{b}	3.1^{b}	2.8^{b}	3.0^{b}	2.4^{a}	3.0	0.11	9
AHU # 3	3.2^{b}	3.3^{b}	2.9^{b}	2.9^{b}		3.8^{b}	2.9^{b}	2.8^{a}	2.8^{a}	2.8^{a}	3.0	0.10	9
AHU # 135	3.3^{b}	3.5^{b}	2.8^{a}	3.0^{b}	3.4^{b}		4.0^{b}	2.8^{a}	3.2^{b}	3.1^{b}	3.2	0.13	9
RTU/DX # 10	3.2	3.7	2.9	3.2	3.0	3.6	3.7	3.8		3.1	3.4	0.12	7
RTU/DX # 9	3.3	3.8	3.0	3.2	3.0	3.4	3.8	3.6	3.1	3.2	3.3	0.09	8
RTU/DX-AHU # 132	3.6^{a}	3.4^{a}	2.8^{a}	3.1^{a}	2.9^{a}	4.2^{b}	4.3^{b}	3.4^{a}			3.3	0.16	7
RTU/DX-AHU # 135	4.1	4.3	3.1	3.7		4.0	4.5	3.6			3.9	0.09	5
FCU UNIT # 4		3.7^{b}	3.0^{a}	3.0^{a}		4.3^{b}		3.2^{a}			3.4	0.19	5

[*] AHU = air-handling unit, RTU/DX = rooftop unit with direct expansion, FCU = fan coil unit. Different superscripts indicate a difference at the $p < 0.05$ level of significance. SE = standard error. N = number of assessors rating the equipment.

Survey Evaluation

A trial was set up whereby ten assessors evaluated 200 components from two major HVAC systems that were situated in two different geographical locations on the same day. Professionals from three independent companies were the assessors. To determine if there was a range of operating conditions in the HVAC equipment, the authors had previously evaluated the components. Components were found to range between scores of 1.0 and 5.0. The assessors were technicians with varying degrees of expertise in either HVAC mechanical or HVAC control systems or indoor air quality technicians. Experience of the assessors ranged from 4 to 40 years. A two-hour informational session was provided to the assessors, which was intentionally designed to introduce the survey form without implying what ratings should be assigned during the inspections. During the two-hour session, assessors were instructed as to which equipment was to be surveyed, told not to collaborate with each other, and told to stay within the confines of their expertise and principles of the survey system.

Statistical Analysis

Component scores for each category were averaged to give an average category score per assessor. Category means across assessors were then analyzed using a one-way analysis of variance (ANOVA) after the data had been checked for normality and equality of variance. A Tukey post-hoc analysis was performed on all significant results (Sigma Stat 2.03 SPSS, ILL). A Cronbach's Alpha Internal Consistency analysis was conducted on the ratings given by the assessors. This procedure provides a measure of rating reliability (SAS 8.2, North Carolina).

RESULTS

The results for the trial are shown in Tables 2 and 3. Table 2 presents expanded data, whereas Table 3 presents a more concise summary.

Results from Table 2 demonstrate that there were significant differences between assessors ($P < 0.05$) for 9 of the 11 categories examined. In these nine categories, a trend was evident whereby assessors 6 and 7 who had the most experience (around 40 years) assigned higher ratings to the equipment than assessor 5 with four years of experience.The results of assessors 6 and 7 on the first two surveyed AHUs showed that higher scores were applied to the three subcategories of (1) fans, motors, service, (2) coils, filters, belts, gauges, alarms, etc., and (3) condensate systems, drains, pans, etc. These higher scores increased their average score for that category. The result from the Cronbach's Alpha Internal Consistency analysis was 0.76, indicating a good agreement between assessors.

Table 3 shows that for 10 of 13 categories there were significant differences between assessors. The average range between assessors in these categories was 2.7-3.8. The overall CME for both school HVAC systems was 3.3. In this exercise, weightings were not applied to the categories or components.

DISCUSSION

The higher scores given by the more experienced assessors may be due to the fact that these assessors paid more atten-

Table 3. Mean Ratings from an Investigation of the HVAC System of One School by Up to Ten Assessors Using a New Survey Rating System*

Category	Mean	SE	P value	N
Cold Water System	3.6	0.17	<0.05	9
Chiller System	3.2	0.09	>0.05	9
AHU Library	3.3	0.18	>0.05	5
AHU D-Wing	3.3	0.11	<0.05	10
AHU E-Wing (1)	3.4	0.12	<0.05	10
AHU E-Wing (2)	3.3	0.17	<0.001	9
AHU Administration	3.3	0.10	>0.05	9
AHU Multi-zones	3.3	0.11	<0.001	10
RTU/DX Unit 3	3.4	0.10	<0.05	10
RTU/DX Unit 10	3.4	0.11	<0.05	10
FCU Unit 8	3.1	0.10	<0.001	5
FCU Unit 3	3.2	0.10	<0.001	6
FCU Unit 10	3.2	0.10	<0.001	6

* AHU = air-handling unit, RTU/DX = return air-handling unit, direct expansion, FCU = fan coil unit. A P value of greater than 0.05 indicates that there are no significant differences between means at the 0.05 level. SE = standard error. N= number of assessors rating the equipment.

tion to smaller details inside the categories and therefore saw more components that were not functioning optimally. The design of the survey is such that this issue can be overcome to a degree through the addition of more subcategories inside the major categories, allowing for less experienced assessors to check these smaller details.

Other checklists have been developed for HVAC systems; for example, Persily (1993) presented a method whereby the HVAC system is inspected as part of an overall building system and most standard texts provide detail on HVAC fault analysis (e.g., Kreider 2001). This survey technique differs from these other approaches in that it provides a numerical output that helps in providing a concise interpretation as to the status of the HVAC system.

Katipamula et al. (2001) list five requirements for methods of HVAC predictive maintenance, and these requirements have application to this survey. The requirements are that (1) the system must identify abnormal systems accurately, (2) the system must not give false alarms, (3) the system must report the levels of confidence associated with each diagnosis, (4) the system must rank the conclusions, and (5) the system must be able to cope with insufficient data. The format and nature of the survey addresses requirements 1, 4, and 5. However, requirements 2 and 3 are dependent on the skill and experience of the assessor.

To evaluate a building in terms of sick building syndrome (SBS) status, an indoor occupational survey in conjunction with an overall building inspection and this HVAC survey can provide the basis for a comprehensive assessment. Many studies have shown the association between poor HVAC operation and indoor air quality. For example, Seppanen and Fisk (2002) have shown that air conditioning can be consistently associated with a statistically significant increase in the prevalence of SBS symptoms. Hiipakka and Buffington (2000) reported on the critical role that HVAC systems play with regard to reducing fungal numbers in indoor environments, and Pejtersen et al. (2001) detailed an intervention study that involved the renovation of an HVAC system, consequently leading to significantly reduced complaints from the occupants. This association has been reported for some time. For example, Rask and Lane (1989) reported that improving HVAC maintenance procedures in conjunction with other housekeeping procedures will lead to improved indoor air quality.

CONCLUSION

This paper presents a survey technique for evaluating HVAC systems. The technique is methodical and flexible, has strong internal consistency, and appears able to be successfully used by a wide range of assessors.

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