*Fourth International Conference on Construction in the 21st Century (CITC-IV)*
*"Accelerating Innovation in Engineering, Management and Technology"*
*July 11-13, 2007, Gold Coast, Australia*

# Maintainability Aspects of Central Chilled Water HVAC System

M.Y.L. Chew
*Vice Dean (research, Department of Building, School of Design and Environment, National University of Singapore, Singapore*

Sutapa Das
*Doctoral Candidate, Department of Building, School of Design and Environment, National University of Singapore, Singapore*

## Abstract
Heating ventilation and air-conditioning (HVAC) system is often operated and maintained inefficiently due to the knowledge gap between design guidelines and maintenance practices aided with fault detection techniques. To address this issue and to develop a guideline for good practices, this study examined the maintainability parameters for central chilled water HVAC system - most common option for modern buildings. During site investigations at eight commercial buildings in Singapore, six major components of HVAC system were studied and 87 common defects, their causes and consequences were identified. Among those, 60 were short-listed as significant, based on a questionnaire survey of 40 facility managers and maintenance personnel who ranked the common defects for frequency and impact on economy, system performance, indoor environmental quality and occupants' health and well-being. A parallel study on three buildings was focused on tangible cost implications including repair, replacement, liability and premature failure. Both surveys concluded that design followed by operation and maintenance practices were crucial. Air handling unit and/or fan coil unit was the most critical component causing 30% defects and 48.2% of total cost. Based on this research, a comprehensive guideline for good practices was developed including 48 parameters related to the whole lifecycle of HVAC system.

## Keywords
Building Defects, Commercial Buildings, HVAC System, Life Cycle Cost, Maintainability.

## 1. Introduction

Heating, ventilation and air-conditioning (HVAC) system or more precisely air conditioning and mechanical ventilation (ACMV) system has become almost indispensable in commercial buildings in tropical climate for controlling the indoor environment quality (IEQ). It is one of the most expensive services to operate and maintain especially when system complexity increases with building volume and sophisticated design. Typically, 50-80% of total cost of a project is spent during in-service life and maintenance costs approaches nearly one-third of all the operating costs (Blanchard and Lowery, 1969). Various problems may occur in the long-term running of HVAC systems (Yu and Passen, 2000), such as mold growth in supply air duct affecting occupants' health (Kitter, 1996), the loss of comfort and an approximate 15-30% wastage of energy (Katipamula and Brambley, 2005).

Design guidelines for HVAC system are abundant (ASHRAE, 2004; Bearg, 1993; Mull, 1997; Ross, 2004) along with (1) system performance aspects such as, ventilation (ASHRAE, 2001b); safety (ASHRAE, 2001b); indoor air quality (ENV, 1996); control of biological fouling (ENV, 2001), noise and vibration control (Schaffer, 1991) and (2) components, namely, ductwork (Gill, 2000; HVCA, 1982; SMACNA, 1995); diffuser (Int-Hout, 2004); chiller plant (Law, 2003);, cooling tower (Stanford,2003).

On the other hand, studies on system maintenance had been developed around three major concepts, namely, breakdown maintenance, time-based maintenance and condition-based maintenance (Yoshimura and Ito, 1989). Fault detection and diagnosis (FDD) for system performance had been modeled by International Energy Agency (Dexter and Pakanen, 2001; Liang and Du, 2006) along with advanced algorithm such as multi-step fuzzy model (Dexter and Ngo, 2001); general regression neural networks (Lee, House and Kyong, 2004); transit pattern analysis (Cho et.al, 2005) etc. A detailed analysis of sub-systems had been carried out for: (1) sensors (Hou et al, 2006; Wang and Xiao, 2004) and (2) air handling units (Pakanen and Sandquist, 2003; Yoshida and Kumar, 1999; Yoshida, Kumar and Morita, 2001).

From the review of the past works, it was identified that in spite of advanced design and fault detection techniques, HVAC systems waste energy and defects are prevalent. This is due to the knowledge gap between design guideline and maintenance aided with FDD. To bridge this gap, consideration for maintainability aspect in all phases of system lifecycle is highly essential. Shrinking maintenance budgets, increasingly competitive markets and rising utility bills have heightened the concern about the operation, maintenance and repair (OM&R) cost and hence, maintainability has become an issue of paramount importance (Bourke and Davies, 1997). The traditional designation of 'necessary evil' of maintainability had been replaced by Dunston and William (1999) as the design characteristics which integrates function, accessibility, reliability and ease of servicing and repairs, that minimizes costs, and maximizes benefits of the expected life cycle value of a facility. The meaning was further extended to "achieving the optimum performance throughout the building life span within a minimum life cycle cost" (Chew and De Silva, 2003). This study was conducted to identify the common defects, their causes and implications for central chilled water HVAC system. The main aim was to develop a guideline for good practices such that the maintainability aspect is addressed in every phases of system's effective life span, hence lowering the total lifecycle cost.

## 2. Research methodology

### 2.1 Data collection

In most of the commercial buildings of Singapore, central chilled water type system is used as it has many advantages in terms of energy and cooling capacity over direct expansion (DX) system. In the first phase of data collection, a preliminary field survey was conducted in eight big commercial buildings with central chilled water HVAC system. Discussion with facility managers (FM) and maintenance personnel was followed by walk-through and photo documentation of major components such as the air handling unit (AHU), fan coil unit (FCU), chiller plant, cooling tower, controls, ducting and terminal units. These defects were analyzed with the help of information provided by FMs or from available literature (ASHRAE, 2000; Bearg, 1993; Stanford, 2003) along with their causes and four major consequences on: (1) economy, (2) system performance, (3) indoor environmental quality (IEQ) and (4) occupants' health & well-being. These impacts were defined as:

- Economic loss: considerable financial damages sustained as a result of the defect. For example, high cost of replacement of plaster board ceiling due to overflowing of water from the condensate pan.
- System performance loss: such loss occurs when the system performs significantly below normal operating efficiency due to the defect. E.g. insufficient air flows due to choked filter in AHU.
- IEQ loss: deterioration of the normal building environment experienced by the building occupants due to the defect. For example, an increase in the room temperature that is due to a defective ducting damper.

- Human health loss: affected health of the building occupants and maintenance personnel as a result of the defect. For example, fatal legionella contamination due to biological fouling in cooling tower

The defect data was incorporated in an detailed survey questionnaire In the first section, the FMs were asked to indicate the frequency of the defect in a five point Likert scale, where 1 = 'rare', 2 = 'sometimes', 3 = 'quite often', 4 = 'very often' and 5 = 'always'. In the second section of the questionnaire, the respondents were asked to indicate the significance of the defects in terms four consequences. As an example the questionnaire for chiller plant is shown in Figure 1. For the second survey, same eight commercial buildings were investigated for preliminary data and among them three were selected for in-depth study.

| **Defects for Cooling Tower** | | | **Frequency** | **Impacts** | | | |
|---|---|---|---|---|---|---|---|
| **Sub-component** | **Description of Defect** | **Probable Causes of the Defect** | **1= Rare<br>2= Sometimes<br>3= quite often<br>4= very often<br>5= Always** | **Economy** | **Sys. Perf.** | **IEQ** | **Health** |
| Fill | Biological fouling | Inadequate cleaning, improper water treatment | | | | | |
| Collection basin | Corrosion | Constant contact with condenser water damages protective layer | | | | | |
| | Biological fouling | Inadequate maintenance of lower basin, improper water treatment | | | | | |
| Condenser water | Foaming | Excess chemical for water treatment, bacteria boom | | | | | |
| Louvers | Corrosion | Constant contact with condenser water and external environment, loss of protective layer. | | | | | |
| Drift eliminator | Biological fouling | Inadequate cleaning, improper water treatment | | | | | |
| Location | Short circuiting | Obstructing structures nearby | | | | | |
| | Intake of warm air from other sources | Wrong position near other exhausts | | | | | |
| Performance | Flow rate too high for heat rejection | Condenser water pump is over supplying condenser water | | | | | |

**Figure 1: Survey Questionnaire for Cooling Tower**

### 2.2 Data analysis

Mean ratings for determining the level of seriousness of the defects were calculated from the feedback received. For each of the 87 defects, the mean level of frequency of occurrence was calculated (Equation 1) and statistical t-test of the means was performed to select the most frequent defects.

$$\text{Mean frequency of occurrence } \overline{X}_{FR} = \sum_{l=1}^{5} i \times n_i \Big/ \sum_{l=1}^{5} n_i \qquad (1)$$

Where, i = frequency rating.

$n_i$ = number of responses for i-th rating

Mean rating for impacts on four aspects, namely, economy, system performance, IEQ and health & well-being were denoted by $\overline{X}_{EC}$, $\overline{X}_{SP}$, $\overline{X}_{EN}$ and $\overline{X}_{HW}$ respectively. For each defect, the relevant consequence(s) were marked with 'yes' with a weightage 1. The irrelevant consequences were marked with 'no' carrying 0 weightage. The mean for consequence rating were calculated by the general formula:

$$\text{Mean consequence rating} = \frac{\sum \text{No. of 'Yes'} \times 100}{\text{Total no. of sample}} \% \tag{2}$$

Cost implications could be of four types, namely, rectification, replacement, liability and premature failure costs. So for any defect, these costs were $C_{REC}$, $C_{REP}$, $C_{PRE}$ and $C_{LIA}$ respectively. The liability cost i.e. losses due to injury or death occurs seldom. As the defects can be frequent or rare but costly, to bring both into a common parameter, the term 'age of the building' Y was incorporated for cost calculation.

$$C_{PRE} = \frac{\text{Expected life span} \times \text{Actual life span}}{\text{Expected life span}} \times \text{Cost of component} \tag{3}$$

Expenditure C for i-th defect is calculated as:

$$C_i = (C_{REC} \times g_{REC} + C_{REP} \times g_{REP} + C_{PRE} \times g_{PRE} + C_{LIA} \times g_{LIA}) / Y \tag{4}$$

$$\text{Cost significance of any defect } \overline{C}_i = \frac{\sum_{i=1}^{n} C_i}{n} \times 100\% \tag{5}$$

Where, g= number of occurrence since the building is commissioning
Y= age of the building.
n = total number of significant defects

## 3. Results and Discussion

The first survey had identified total 87 defects related to six major components of central chilled water HVAC system, out of which 60 were found serious (Table 1). Among those 18 were referred by FMs as frequent and 26 occurs in two or more categories. Economy, system performance, IEQ and health & wellbeing were affected by 19, 31, 28 and 13 defects respectively.

**Table 1: Summary of Major Defects in HVAC System**

| Component | Sub-component | Serious defects | Total defect | Frequent defects | $\overline{X}_{FR}$ |
|---|---|---|---|---|---|
| AHU | Fan | Broken /cracked fan belt, burnt smell from belt, break-down of motor, noisy fan, excessive vibration in motor | 18 | − Clogged inlet filter<br>− Short circuiting<br>− Pressure drop<br>− Broken fan belt<br>− Overflowing drip pan | 3.90<br>3.87<br>3.80<br>3.43<br>3.30 |
| | Cooling coil | Corrosion, scaling, dust deposit, bio-film formation, leakage, excessive airflow causes moisture carryover | | | |
| | Condensatepan | Drip pan overflow, bio-film formation | | | |
| | Air intake | Polluted or exhaust air sucked back | | | |
| | Air filter | Clogging, pressure drop across filter | | | |
| | Actuator | Leakage of chilled water | | | |
| | Accessibility | Difficult / no access for maintenance | | | |
| FCU | Fan | Break-down of motor | 12 | − Pressure drop across filter<br>− Short circuiting | 3.90<br>3.80 |
| | Cooling coil | Scaling, dust deposit, bio-film, excessive airflow causes moisture carryover | | | |

| Compo-nent | Sub-component | Serious defects | Total defect | Frequent defects | $\overline{X}_{FR}$ |
|---|---|---|---|---|---|
| | Condensatepan | Drip pan overflow, bio-film formation | | −Clogged inlet filter | 3.77 |
| | Air intake | Polluted or exhaust air sucked back | | −Dusty cooling coil | 3.50 |
| | Air filter | Clogging, pressure drop across filter | | −Overflowing drip pan | 3.50 |
| | Actuator | Jamming | | | |
| | Accessibility | Difficult / no access for maintenance | | | |
| Chiller plant | Chiller | Scaling, refrigerant leakage, air entry | 10 | −Scaling | 3.97 |
| | Compressor | Excessive vibration and noise, wearing, excess or shortage of oil | | −Condensation of water pipe | 3.97 |
| | Piping | Condensation of water pipe, leakage in tube, damaged monitoring socket | | | |
| | Accessibility | Difficult / no access for maintenance | | | |
| Cooling tower | Fill | Biological fouling | 6 | −Bio-fouling of fill | 4.00 |
| | Collection | Biological fouling | | −Bio-fouling of drift eliminator | 3.90 |
| | Drift eliminator | Biological fouling | | | |
| | Location | Short circuiting, intake other exhaust air | | | |
| | Performance | Flow rate too high to reject heat properly | | | |
| Air dist. & terminal systems | Supply / return ducts | Mold growth, condensation, air leakage, jammed dampers, noise & vibration | 11 | −Mould growth | 3.90 |
| | diffusers / return grille | Blockage, short circuiting, condensation on diffuser, dumping of cold air | | − Condensation on diffuser | 3.53 |
| | VAV box | Drifting off of the sensor settings, faulty pneumatic control | | | |
| Controls & IEQ | General | Poor sensitivity of thermostat, fungus growth on walls, condensation on walls | 3 | −Poor sensitivity of thermostat | 3.90 |

**Table 2: Summary of Cost Significance of Major Defects**

| Component & Number | Defect | $\overline{C}_i$ | Total |
|---|---|---|---|
| AHU /FCU | Overflowing condensate pan | 16.9% | 48.2.% |
| | Dust accumulation on coil | 7.5% | |
| | Leakage in condenser tubing | 7.3% | |
| | Corrosion of cooling coil | 5.9% | |
| | Lack of ease of accessibility | 5.8% | |
| | Dust and bio-film on cooling coil | 1.8% | |
| | Motor/blower failure | 1.8% | |
| | Damaged fins | 1.2% | |
| Chiller | Noise in chiller plant room | 13.3% | 24.0% |
| | Condensation on piping insulation | 5.7% | |
| | Corrosion in piping | 3.7% | |
| | Fouling in condenser tubing | 1.3% | |
| Air distribution & terminal systems | Dead Spaces | 5.5% | 13.4% |
| | Return air path obstructed | 3.0% | |
| | Condensation at duct | 2.5% | |
| | Air dumping | 2.4% | |
| Controls | Lack of precise temperature control | 7.2% | 8.2% |
| | Poor response to changing IEQ | 1.0% | |

From the second survey, 34 major defects were identified during in-depth case studies. Some defects that were not found in the case studies were either had been prevented by good practices or required nominal expenditure, hence were not taken into account for costly rectifications according to the respective FMs. Next, the cost significance of three buildings was averaged. Out of 34 serious defects, only 18 defects have cost significances of 1% or more totaling up to 93.8% (Table 2). Though AHU /FCU were associated with 30% of major defects, but it incurred 48.6% of total O&M cost.

It was found that these defects could have been be prevented by considering five major maintainability criteria, namely, design, appropriate material selection, construction practices, operation & maintenance (O&M) practices and environmental factors. It is important to know at which stage what are the defects arise so that the appropriate preventive measures can be taken to improve the maintainability. Based on local codes and recommendation set by international bodies like ASHRAE and SMCNA, a guideline for 48 good practices was mentioned under these five criteria (Table 3). It is found that maintainability concept had maximum benefit when adopted in design stage and next most important stage was O&M.

**Table 3: Guideline for Good Practices**

| Criteria | Component | Sub-Comp. | Factors |
|---|---|---|---|
| Design (26) | | | System Selection |
| | AHU/FCU | Filter | Filter selection and disposability, layer detail |
| | | Drainage | Condensation drainpipe and insulation detail, use of secondary drain-pan, drainpipe support detail |
| | | AHU room | Location selection, mech. equipment room detail |
| | | Suspended unit | Equipment location detail, access panel detail |
| | Air distribution system | Air inlet | Location selection, ventilation |
| | | Air terminals | General design, location detail, diffuser selection |
| | | Duct liner | Thickness detail |
| | Piping | | Piping joint selection, insulation Detail |
| | Chiller | | Details (plant room safety, location, multiple chiller installation), use of auto tube cleaning system |
| | Cooling tower | | Location detail |
| | Controls | | Control selection, thermostat location detail |
| Material (3) | AHU / FCU | | Condensate drain-pan material selection |
| | Piping system | | Insulation selection |
| | Cooling tower | | Material selection |
| Construction (7) | AHU | | Cooling coil flushing detail |
| | Air delivery | | Detail (construction, insulation), pressure testing |
| | Piping system | | Installation detail, pressure testing, insulation |
| O&M (11) | All | | Regular inspection and cleaning (cooling coil, condensate drain pan, UVC devices, filter, chiller, fan / motor, cooling tower, piping), use of fungicide, proper water treatment, vibration analysis. |
| Environment (1) | | | Temperature set point |

## 4. Conclusions

The study had identified 60 persistent defects out of total 87 defects commonly occurring in six major components of central chilled water HVAC system. The analysis was based on (1) frequency of occurrence of various defects and (2) seriousness of the defects in terms of their adverse effect on economy, system performance, indoor environmental quality and occupants' health & well-being. A parallel in-depth case study conducted on three buildings concluded 18 out of 60 significant defects had serious cost implication due to replacement, rectification, liability and premature failure. Air handling unit and/or fan coil unit was found to be the most critical component causing 30% defects and 48.2% of total cost. Both the surveys established that addressing maintainability aspects was most effective during design, next comes by operation and maintenance practices, followed by construction quality, material selection and environmental issues. This information was reflected in the comprehensive guideline for good practices, in which 48 parameters are proposed to cover all phases of system's life cycle.

## 5. Acknowledgement

Significant contribution in data collection was made by undergraduate students Wee Sean Han Adrian and Fu Ailian.

## 6. References

ASHRAE (2004). *ASHRAE Handbook. HVAC Systems and Equipment.* Atlanta, G.A.: American Society of Heating, Refrigerating, and Air-Conditioning Engineers.

ASHRAE (2001a). *Safety Standards for Refrigeration Systems.* ANSI/ASHRAE 15-2001. Atlanta. G.A.: American Society of Heating, Refrigerating, and Air-Conditioning Engineers.

ASHRAE (2001b). *Ventilation for Acceptable Indoor Air Quality*. ASHRAE Standards 62-2001. Atlanta, G.A.: American Society of Heating, Refrigerating and Air-conditioning Engineers.

Bearg, D.W. (1993). *Indoor Air Quality and HVAC systems.* Boca Raton US: Lewis Publishers.

Blanchard, B.S., and Lowery, E.E. (1969). *Maintainability: principles and practices*. New York: McGraw-Hill Inc.

Bourke, K. and Davies, H. (1997). "*Factors affecting the service life productions of buildings: A discussion paper"*. Laboratory Report. Prepared for Building Research Establishment, Garston, U.K.

Chew, M.Y.L., and De Silva, N. (2003). "Maintainability problems of wet areas high-rise residential buildings". *Building Research and Information.* Vol..31, No. 1, pp 59-69.

Cho, S.H., Yang, H.C., Zaheer-uddin, M. and Ahn, B.C. .(2005). "Transient pattern analysis for fault detection and diagnosis of HVAC system". *Energy Conversion and Management.* Vol. 46, pp 3103–3116.

Dexter, A. and Pakanen, J. (Editors). (2001). "Demonstrating automated fault detection and diagnosis methods in real buildings, IEA Annex 34", Espoo, VIT Symposium., Finland: 2001.

Dexter, A.L. and Ngo, D. (2001). "Fault diagnosis in air-conditioning systems: a multi-step fuzzy model approach", *International Journal of HVAC&R Research.* Vol. 7, pp 83–102.

Dunston P.S., and William C.E (1999). "Incorporating maintainability in constructability review process". *Journal of Management in Engineering.* Vol. 15, No.5, pp 56-60.

ENV (1996). *Guidelines for Good Indoor Air Quality in Office Premises.* Singapore: Institute of Environmental Epidemiology, Ministry of the Environment.

ENV (2001). *Code of Practice for the Control of the Legionella Disease* (4th Ed.). Singapore: Institute of Environmental Epidemiology, Ministry of the Environment.

Gill, K.E. (2000). "*Opportunities and Challenges in New Piping and Insulation"*. HPAC. Vol. 73, No. 8, pp 43-48.

Hou, Z.J., Lian, Z.W., Yao, H. and Yuan, X.J. (2006). "Data mining based sensor fault diagnosis and validation for building air conditioning system". *Energy Conversion and Management*. Vol. 47, pp 2479–2490.

HVCA (1982). *DW/142 Specification for Sheet Metal Ductwork: Low, Medium, and High Pressure/Velocity Air Systems*. London: Heating and Ventilating Contractors' Association.

Int-Hout, D. (2004). "Best practices for selecting diffusers". *ASHRAE Journal.* Vol.45, No.6, pp 24-28.

Katipamula, S, Brambley, M.R. (2005). "Methods for fault detection, diagnostics, and prognostics for building systems-a review, part I". *Int. Journal of HVAC&R Research.* Vol. 11, pp 3-25.

Kitter, R. (1996). "Mechanical dehumidification control strategies and psychometrics". *ASHRAE Transactions.* Vol. 102, pp 613-617.

Law, S. (2003). "HVAC Plant Selection Based on Life Cycle Analysis". *Proceedings of CIBSE Conference.* London: The Chartered Institution of Building Services Engineer.

Lee, W.Y., House, J.M. and Kyong, N.H. (2004). "Subsystem level fault diagnosis of a building's air-handling unit using general regression neural networks". *Applied Energy.* Vol. 77, pp 153–170.

Liang, J. and Du, R. (2006)."Model-based fault detection and diagnosis of HVAC systems using support vector machine method". *International Journal of Refrigeration.* Accepted manuscript.

Mull, T.E. (1997). *HVAC Principles and Applications Manual.* New York: McGraw-Hill.

Pakanen, J.E. and Sundquist, T. (2003). "Automation-assisted fault detection of an air-handling unit; implementing the method in a real building". *Energy and Buildings.* Vol. 35, pp 193–202.

Ross, D.E. (2004), *HVAC Design Guide for Tall Buildings*. Atlanta, GA: American Society of Heating, Ventilation and Air-Conditioning Engineers Inc.

Schaffer, M.E. (1991). *A Practical Guide to Noise and Vibration Control for HVAC systems.* Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

SMACNA (1995). *HVAC Duct Construction Standards – Metal and Flexible*. Virginia: Sheet and Air conditioning Contractors' National Association, Inc.

Wang, S.W. and Xiao, F. (2004). "Detection and diagnosis of AHU sensor faults using principle component analysis method". *Energy Conversion and Management*. Vol. 45, pp 2667–2686.

Yoshida, H. and Kumar, S. (1999). "ARX and AFMM model-based on-line real-time data base diagnosis of sudden fault in AHU of VAV system". *Energy Conversion and Management*. Vol. 40, pp 1191–1206.

Yoshida, H., Kumar, S. H. and Morita, Y. (2001)."Online fault detection and diagnosis in VAV air handling unit by RARX modeling". *Energy and Buildings.* Vol. 33, pp 391–401.

Yoshimura, M. and Ito, N. (1989). "Effective diagnosis methods for air conditioning equipment in telecommunication buildings". *Proceedings of Eleventh International Telecommunications Energy Conference*. Florence, Italy.