IMPACT OF MAINTENANCE MANAGEMENT PROCEDURES ON ENERGY EFFICIENCY OF CHILLERS

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ABSTRACT

The most important element of the central air conditioning system, the chiller, accounts for about 40% of annual total energy consumption of commercial and industrial buildings. As a result, many approaches have been proposed to increase energy efficiency of chillers with the intention of managing the annual total energy consumption of facilities. Among them, it was revealed that the approach of proper chiller maintenance procedures lead towards the energy efficiency of chillers. Therefore, the research was focused on identifying the impact of maintenance management procedures on energy efficiency of chillers.

The data was collected through a pilot survey and a main survey which were followed by a questionnaire along with observations and interviews with experienced industry practitioners.

It was identified that the maintenance procedures has a great impact towards the energy efficiency of chillers. Perform condenser water quality test, Monitoring refrigerant pressure and temperature, Monitoring water flows, cleaning of condenser bundle and cooling tower cleaning and water treatment were identified as the most significant maintenance activities which assist to meet the standard energy efficiency level of chillers. Eventually, a multiple linear regression model was developed with the intention of deriving relationship between performance deviation of above maintenance activities and energy efficiency drop of chillers.

Keywords: *Chillers; Energy Efficiency; Energy Efficiency Drop; Maintenance Management Procedures; Maintenance Performance Deviation.*

1. INTRODUCTION

As a rule of thumb, the air conditioning systems used in commercial and institutional buildings can account for more than 50% of the total electricity consumption (Jayamaha, 2007). Thereof, Chan et al. (2009) states that the most important part of a central air conditioning system, the chiller accounts for more than 60% of power consumption of central air conditioning system. Further, it is proved by Lee and Lee (2010) in a recent article indicating that chillers alone may already account up to 35-40% of annual electricity consumption. By analysing above data, it can be argued that the chiller of any air conditioning system approximately compensates 30% of total energy consumption of a facility and it creates a considerable necessity to pay attention on achieving the energy efficiency of chillers.

Therefore, this research was focused on identifying the impact of maintenance procedures towards achieving the energy efficiency of chillers and it was limited to the chiller plants of five star hotels in Colombo metropolitan area.

2. FACTORS AFFECTING THE ENERGY EFFICIENCY OF CHILLERS

Efficiency of a chiller is measured by how many units of power are used to produce one unit of cooling (Jayamaha, 2007).

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$$Chiller\ Efficiency = \frac{Power\ Input(\mathrm{kW})}{Cooling\ Produced\ (RT)} \quad \text{(Eq:01)}$$

However, it is evident in the literature that several factors can be affected the energy efficiency of chillers. Chan (2004 cited Chan *et al.*, 2009) reveals seven such factors namely partial load condition, external environment condition, chilled water flow, chilled water supply temperature, condensation super cooling, evaporation superheating, and preset compressor temperature. Partial load condition is one of them, which has a greater impact on efficiency of chillers (Yu and Chan, 2009). It is proved by Yu and Chan (2009) that, when the cooling load of a building is changed throughout its occupied period, chillers tend to operate frequently at part load and this kind of operation will cause chiller efficiency to drop and such drop becomes considerable when the set point of condensing temperature is fixed at a high level while outdoor temperature is low. Variation of weather condition (external air temperature and relative humidity) is the other factor which strongly influence on efficiency of chiller (Yu and Chan, 2005). In an article, Yu and Chan (2007), has proved it by stating that'impact of weather and external environment condition (external air temperature and relative humidity) affect the energy efficiency of chillers through fluctuating the cooling load'.

Further, with the improvements of the design of chillers, Jayamaha (2007) expresses that efficiency of chillers have been improved and it is about averagely 44% over the period of last 30 years. Therefore, it can be argued that design of chillers also affect the efficiency of chillers.

Chiller maintenance is another factor which affects the energy efficiency of chillers. That is proved by Lewis and Riley (2011) stating that 'proper maintenance is necessary to achieve optimal energy performance, while energy performance data is needed for effective maintenance management'. Accordingly, in next section it is focused on what kind of maintenance procedures have been introduced by various organizations in order to achieve the efficiency of chillers.

3. MAINTENANCE OF CHILLERS

As it is discussed earlier, chiller maintenance has a great impact on its efficiency. Therefore, many organizations have introduced various chiller maintenance procedures based on various categories. For instance, American Society of Heating Refrigeration and Air- conditioning Engineers (ASHRAE) (2004) introduces two chiller maintenance procedures based on two categories in ASHRAE Handbook-HVAC Systems and Equipment. One is based on components of the chiller namely compressor, condenser and evaporator and other one is on types of maintenance namely continual monitoring, periodic checks, regularly scheduled maintenance and extended maintenance checks. In addition to that, U.S Department of Energy (2010) has also introduced a list of recommended maintenance procedures for chiller maintenance. Furthermore, recommended maintenance procedures published by McQuay International (2005) and Trane Inc (2005) can be shown as two examples for maintenance procedures introduced by chiller manufactures for chiller maintenance.

4. RESEARCH METHODOLOGY

A comprehensive literature survey was carried out referring to journals, books and other published documents to obtain existing knowledge on factors affecting energy efficiency, maintenance procedures of chillers, and the researchable gaps towards the relationship between the maintenance management procedures and energy efficiency of chillers,.

Through a pilot survey which was carried out among industrial specialists (air conditioning consultants), the factors affecting energy efficiency of chillers which were discovered through past literature were assessed and established. And further, it was prioritized the identified 31 maintenance activities towards the energy efficiency of chillersthroughalikert scale questionnaire consisted with 1-5 rating scalewhere, 1 = very little important, 2 = little important, 3 = average important, 4 = high important, 5 = extremely important. As the number of well experienced and well expertise air conditioning consultants engage with chiller systems are hardly found, 4 numbers of air conditioning consultants were selected as sample of specialists for the pilot survey.

The practicing level of the identified 31 maintenance activities (PLMA) of chillers and current energy efficiency of chillers were identified through the main survey.The practicing levels of chillersalso were recognized using a likert scale questionnairewhere the rating scale is similar as above and current energy efficiency of chillers were identified through interviews and observations of past records.The survey sample was established based on number of the chillers operate in Colombo city hotels. Accordingly, 14 chillers in 07 five star hotels were selected as the sample for the main survey which was deemed to be the target population of the study.

Statistical tests using Statistical Package for Social Sciences (SPSS) software were carried out to analyse the data. Further, multiple regression modelling was used to establish a relationship between energy efficiency (dependent variable) and maintenance activities (independent variables) of chillers.

5. MULTIPLE REGRESSION MODEL

Generally, regression modeling is used to examine the relationship or the behavior of the dependent variable with response to two or more independent variables (Rice, 1995). Accordingly, in this research, a multiple regression model was developed to establish the relationship between the deviation of performance level of required maintenance activities and resultant energy efficiency drop of chillers.

5.1. INPUT OF THE MULTIPLE REGRESSION MODEL

Maintenance Performance Deviations (MPD) of the identified maintenance activities were used as inputs (independent variables) to capture the efficiency loss caused to these deviations due to lack of implementation of such required maintenance activities of chillers. MPD is derived based on the difference between the recommended importance level of maintenance activities of chillers and their current practicing level. MPD was established using the equation 02 as follows.

$$MPD = \frac{ILMA \times (5 - PLMA)}{ILMA \times 5} \times 100 \qquad \text{(Eq: 02)}$$

Where, $ILMA$= importance level of maintenance activities and $PLMA$= the practicing level of maintenance activities.

The importance level (ILMA) and the practicing level (PLMA) of identified maintenance activities were quantified using the mean ratings of respondents' views which were obtained according to the given 1-5 likert scale. Eight (08) maintenance activities were established as significant from the identified 31 activities (Refer Table1). Table 1, 2 and 3 show ILMA, PLMA and MPD values of these maintenance activities respectively.

Table 1: Significant Maintenance Activities and Their ILMA

Significant Maintenance Activities	**Abbreviation**	**Importance Level of Maintenance Activities (ILMA)**
Monitor for condenser tube fouling	MCTF	4.25
Perform condenser water quality test	PCWQT	5.00
Operating conditions logging	OCL	5.00
Monitoring refrigerant pressure and temperature	MRPT	4.75
Monitoring water flows	MWF	5.00
Monitoring water pressure and temperature	MWPT	5.00
Cleaning of condenser bundle	CCB	5.00
Cooling tower cleaning & water treatment	CTCWT	5.00

Table 2: Performance Level of Maintenance Activities

CN	MCTF	PCWQT	OCL	MRPT	MWF	MWPT	CCB	CTCWT
C1	100	20	0	20	0	0	20	20
C2	100	20	0	20	0	0	20	20
C3	100	40	0	40	40	0	40	40
C4	100	40	0	40	40	0	40	40
C5	100	100	0	40	40	0	100	100
C6	100	20	0	20	0	0	40	20
C7	100	20	0	20	0	0	40	20
C8	100	100	0	40	40	0	100	100
C9	100	100	0	40	40	0	100	100
C10	100	40	0	40	40	0	100	40
C11	100	40	0	40	40	0	100	40
C12	100	20	0	20	0	0	20	20
C13	100	20	0	20	0	0	20	20
C14	100	20	0	20	0	0	20	20

Table 3: Performance Deviation Level of Maintenance Activities

CN	MCTF	PCWQT	OCL	MRPT	MWF	MWPT	CCB	CTCWT
C1	100	20	0	20	0	0	20	20
C2	100	20	0	20	0	0	20	20
C3	100	40	0	40	40	0	40	40
C4	100	40	0	40	40	0	40	40
C5	100	100	0	40	40	0	100	100
C6	100	20	0	20	0	0	40	20
C7	100	20	0	20	0	0	40	20
C8	100	100	0	40	40	0	100	100
C9	100	100	0	40	40	0	100	100
C10	100	40	0	40	40	0	100	40
C11	100	40	0	40	40	0	100	40
C12	100	20	0	20	0	0	20	20
C13	100	20	0	20	0	0	20	20
C14	100	20	0	20	0	0	20	20

5.2. *OUTPUT OF THE MULTIPLE REGRESSION MODEL*

As the model was focusing on the Energy Efficiency Drop (EED) of chillers with response to the maintenance performance deviation of maintenance activities, EED was considered as the output of the model (dependent variable). Therefore, the percentage EED was calculated based on the equation 3 as follows.

$$EED = \left(\frac{SEE - EEE}{SEE} \right) \times 100 \qquad \text{(Eq: 03)}$$

Where, SEE = the standard energy efficiency and EEE = the existing energy efficiency

In order to derive the EED of each chiller, standard efficiency of each chiller was taken referring to the chiller manuals, catalogues and chiller name plates during the field observation of the main survey. The existing energy efficiency was calculated using the Equation 01 in Section 02 by using the energy consumption data obtained from the field observation during the main survey.

5.3. *MULTIPLE REGRESSION MODEL*

The model can be mathematically expressed as,

$$Y_i = B_0 + B_i \times X_i + \ldots\ldots\ldots\ldots + B_k \times X_k + e \qquad \text{(Eq:04)}$$

Where, B_0 = coefficient, Bi = the coefficient of i^{th} variable, $X_i \forall I$=1,,,, 8 = identified maintenance activities (refer Table 1), B_k = the coefficient of k^{th} maintenance activity, and e = the error term.

6. RELATIONSHIP BETWEEN MPD LEVEL AND EED

MPD levels derived in Table 3 and EED which was calculated according to Equation 3 can be shown as a summery in Table 4 which used for the development of multiple linear regression model.

Table 4: Maintenance Performance Deviation Level and Energy Efficiency Drop

CN	Maintenance Performance Deviation								EED
	MCTF	PCWQT	OCL	MRPT	MWF	MWPT	CCB	CTCWT	
C1	100	20	0	20	0	0	20	20	3.9
C2	100	20	0	20	0	0	20	20	3.6
C3	100	40	0	40	40	0	40	40	11.5
C4	100	40	0	40	40	0	40	40	15.9
C5	100	100	0	40	40	0	100	100	26.9
C6	100	20	0	20	0	0	40	20	8.3
C7	100	20	0	20	0	0	40	20	5.2
C8	100	100	0	40	40	0	100	100	33.8
C9	100	100	0	40	40	0	100	100	24.6
C10	100	40	0	40	40	0	100	40	13.4
C11	100	40	0	40	40	0	100	40	23.8
C12	100	20	0	20	0	0	20	20	7.9
C13	100	20	0	20	0	0	20	20	5.6
C14	100	20	0	20	0	0	20	20	4.6

Correlations of performance deviation of each maintenance activity with the dependent variable were calculated and correlation coefficients were derived (refer Table 5). They can be used as a prior observation on the dependent variable with respect to changes of each independent variable. It was considered the change of one variable at one time to derive the prospected change in the dependent variable.

Table 5: Correlation between Maintenance Performance Deviation and Energy Efficiency Drop

Maintenance Activities		Correlation Coefficient
Monitor for condenser tube fouling	MCTF	0.000
Perform condenser water quality test	PCWQT	0.910
Operating conditions logging	OCL	0.000
Monitoring refrigerant pressure and temperature	MRPT	0.825
Monitoring water flows	MWF	0.825
Monitoring water pressure and temperature	MWPT	0.000
Cleaning of condenser bundle	CCB	0.880
Cooling tower cleaning & water treatment	CTCWT	0.910

According to the correlation coefficients (refer Table 5), except MCTF, OCL and MWPT, all other maintenance activities showed a positive and strong relationship with the energy efficiency drop of chillers where PCWQT, MRPT, MWF, CCB and CTCWT were statistically significant at 98% confidence level.Since MCTF, OCL and MWPT had zero correlation with the energy drop those maintenance activities were rejected by SPSS from the developing process of the model.

6.1. *IMPACT OF MAINTENANCE ACTIVITIES ON THE ENERGY EFFICIENCY*

The regression model was developed based using the maintenance activities which had a positive relationship with EED (refer Table 5). Accordingly, the developed regression model can be expressed as follows.

$$Y = B_0 + B_{PCWQT} \times MPD_{PCQWT} + B_{MRPT} \times MPD_{MRPT} + B_{MWF} \times MPD_{MWF} + B_{CCB} \times MPD_{CCB} + B_{CTCWT} \times MPD_{CTCWT} + e$$

(Eq: 05)

Assumptions Made in Linear Regression

- $E(e_i) = 0$: The random error terms (e_i) are normally distributed with 0 (zero) mean
- $E\left(e_i^2\right) = \sigma_e^2$: The random error has the same variance for all i.
- $E\left(e_i e_j\right) = 0$: The random error term must be independent; there is no correlation across observations

Considering above assumptions, the Equation 05 can be re-written as;

$$Y = B_0 + B_{PCWQT} \times MPD_{PCWQT} + B_{MRPT} \times MPD_{MRPT} + B_{MWF} \times MPD_{MWF} + B_{CCB} \times MPD_{CCB} + B_{CTCWT} \times MPD_{CTCWT}$$

(Eq: 06)

Since MCTF, OCL and MWPT had zero correlation with the energy drop and since, PCWQT and MWF having multicollinearity effect with other activities (refer Table 5), those maintenance activities were rejected by the SPSS when calculating coefficient and regression coefficient and three maintenance activities; MRPT,CCB and CTCWT were remained.

6.1.1. *PARAMETERS OF THE REGRESSION MODEL*

COEFFICIENT OF DETERMINATION

In Multiple Linear Regression modeling, coefficient of determination (R^2) is an evaluation of the overall closeness of the relationship between independent variable and dependent variables and it represents the proportion of variation in Y (EED) which could be explained by variation in X_1 to X_5 and how closely data points cluster around the regression line. Accordingly, in this model the R^2 was obtained as 0.902 and it indicates that there is a strong relationship between MPD of MRPT,CCB and CTCWT maintenance activities and EED.

REGRESSION COEFFICIENTS

Coefficient for the constant denotes the intercept of the regression line and it represents the energy efficiency drop of the chiller when all maintenance activities are being done in an optimum way. Regression coefficients derived from the SPSS for the continuation of the model are shown in Table 6.

Table 6: Regression Coefficients of the Model

Variables/Constant		**Regression Coefficients**
Constant (Intersect)	B_0	-
Monitoring refrigerant pressure and temperature	B_{MRPT}	0.191
Cleaning of condenser bundle	B_{CCB}	0.298
Cooling tower cleaning & water treatment	B_{CTCWT}	0.530

According to the results of Table 6, when all maintenance activities are being done in an optimum way, the efficiency drop is 0.

Coefficients for maintenance performance deviation of each maintenance activity denote the degree of change in energy efficiency drop of chillers with 1% change in performance deviation of each maintenance activity. The results showed, 1% change of performance deviation of MRPT, CCB and CTCWT will impact on the energy efficiency of chillers by 19.1%, 29.8% and 53%.

Therefore, based on regression coefficients as shown in the Table6, the relationship between the MPD and EED of chillers can be illustrated as shown in Equation 07.

$$EED = 0.191 \times MPD_{MRPT} + 0.298 \times MPD_{CCB} + 0.530 \times_{CTCWT} \quad \text{(Eq: 07)}$$

PARTIAL CORRELATION COEFFICIENT

The partial correlations interpret the relationship between dependent variable and each independent variable, when other independent variables are held constant.

Table 7: Partial Correlation

Variables/Constant		Partial Correlation	(Partial Correlation)^2
Monitoring refrigerant pressure and temperature	B_{MRPT}	0.324	0.105
Cleaning of condenser bundle	B_{CCB}	0.425	0.181
Cooling tower cleaning & water treatment	B_{CTCWT}	0.699	0.489

The analysis of the partial correlations shown in Table 7 proved that; the cooling tower cleaning & water treatment is the most important maintenance activity which leads energy efficiency drop.

PART COEFFICIENT

Table 8: Part Correlations

Variables/Constant		Part Correlation	(Part Correlation)^2
Monitoring refrigerant pressure and temperature	B_{MRPT}	0.107	0.011
Cleaning of condenser bundle	B_{CCB}	0.147	0.022
Cooling tower cleaning & water treatment	B_{CTCWT}	0.306	0.094

The part correlation interprets the unique contribution of each independent variable by alone to the dependent variable. Accordingly, the analysis of part correlation illustrated in Table 8 proved that cooling tower cleaning & water treatment is the most effectible maintenance activity.

IMPACT TOWARDS EFFICIENCY DROP BY OVERLAPPING MAINTENANCE DEVIATION

The overlapping impact on the energy efficiency by all maintenance activities was derived subtracting the cumulative of squared of part correlations from the coefficient of determination (R^2). Accordingly, the overlapping impact or the jointly contribution of maintenance activities toward the energy efficiency is 75.5% of the variance of the energy efficiency drop (90.2 – (1.1 + 2.2 + 9.4)).

7. APPLICATION OF THE DEVELOPED MODEL

The developed model was applied to derive the energy efficiency drop of chillers in Colombo city hotels. as shown in Table 9 by using maintenance performance deviations and energy efficiency drop which were illustrated in Table 4 and established 3 maintenance activities by the model namely; MRPT, CCB and CTCWT.

Table 9: Average Performance of the Industry

Chiller No.	MPD_{MRPT}	MPD_{CCB}	MPD_{CTCWT}	B_{MRPT}	B_{CCB}	B_{CTCWT}	$Y = EED$
C1	20	20	20	0.191	0.298	0.530	20.38
C2	20	20	20	0.191	0.298	0.530	20.38
C3	40	40	40	0.191	0.298	0.530	40.76
C4	40	40	40	0.191	0.298	0.530	40.76
C5	40	100	100	0.191	0.298	0.530	90.44
C6	20	40	20	0.191	0.298	0.530	26.34
C7	20	40	20	0.191	0.298	0.530	26.34
C8	40	100	100	0.191	0.298	0.530	90.44
C9	40	100	100	0.191	0.298	0.530	90.44
C10	40	100	40	0.191	0.298	0.530	58.64
C11	40	100	40	0.191	0.298	0.530	58.64
C12	20	20	20	0.191	0.298	0.530	20.38
C13	20	20	20	0.191	0.298	0.530	20.38
C14	20	20	20	0.191	0.298	0.530	20.38
Average	**30**	**54.2857**	**42.8571**	**0.191**	**0.298**	**0.530**	**44.6214**

As shown in Table 9, average industrial maintenance performance deviation MRPT, CCB and CTCWT are 30%, 54.28% and 42.85 respectively. And the respective average energy efficiency drop is 44.62% which makes a huge burden on the energy consumption of the hotel industry and on the national energy supply of the country as well.

Thus, it can be stated that when maintenance performance of MRPT, CCB and CTCWT are deviated from the standard maintenance practice by 30%, 54.2857% and 42.8571% respectively, the energy efficiency of the chillers also affects to deviate from the standard energy efficiency by 44.62% negatively.

8. CONCLUSIONS

Among the factors that affecting the energy efficiency of chillers, maintenance was identified as one of the significant factors which has a great impact on efficiency of chillers. Similarly, among 31 identified important maintenance activities, 08 activities were established as significant for chillers based on the mean ratings. They were Monitoring for condenser tube fouling, Performing condenser water quality test, Operating conditions logging, Monitoring refrigerant pressure and temperature, Monitoring water flows, Monitoring water pressure and temperature, Cleaning of condenser bundle and Cooling tower cleaning & water treatment were selected as the most influencing maintenance activities.

In order to derive the relationship between the maintenance activities and energy efficiency, performance deviation of each maintenance activity for each chiller as the independent variables and respective energy efficiency drop (EED) of each chiller as the dependent variable, were considered to develop the multiple regression model.

Monitoring for condenser tube fouling, Operating conditions logging and Monitoring of water pressure and temperature were rejected from the regression model due to their zero stand deviation and further perform condenser water quality test and Monitoring water flows were removed due to their multicollinearity with others factors. Thus, EED was dependent with three maintenance activities such as Monitoring refrigerant pressure and temperature (MRPT), Cleaning of condenser bundle (CCB) and Cooling tower cleaning & water treatment (CTCWT). It was observed that MRPT, CCB and CTCWT are deviated from the standard maintenance practice by 30%, 54.2857% and 42.8571% respectively, resulting 44.62% drop of energy efficiency of chillers in five star hotels in Colombo city.

Accordingly, the developed model can be used as an influencing tool for industrial practitioners to upgrade their existing chiller maintenance practices and to improve the efficiency performance of their chillers individually. And the model developed using average industrial practices will be a benchmark of the industry to be constructed strategic maintenance practices towards upgrading overall industrial maintenance and energy efficiency performance of chillers.

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