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A Case Study of Electric Chiller Performance Bottleneck Diagnosis by Root Cause Analysis

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***Abstract*—As one of the core cooling equipment in district cooling system, latest electric chiller can achieve high energy efficiency and low CO_2 emission. In recent years, many researches have been conducted on cooling plant performance evaluation and anomaly detection, but very few can quantitatively detect root causes of electric chiller's performance anomaly. In the case study at district cooling plant of UTP (Universiti Teknologi PETRONAS), we adapted RCA (Root Cause Analysis) diagnosis method from steam absorption chiller to electric chiller; developed two bottleneck models for electric chiller's COP (Coefficient of Performance) and CHW (CHilled Water supply) performance diagnosis. By applying new RCA models and method to field trial at UTP campus cooling system, we effectively diagnosed the root cause for electric chillers' performance degradation during period from 2014 to 2015.**

***Keywords*—district cooling, electrical chiller, energy efficiency, root cause analysis.**

I. Introduction

In district cooling industry, electric chiller is used as one of core cooling equipment, because of its high energy efficiency and low CO_2 emission [1]. In Malaysia, electric chillers are installed and operated in most large district cooling plants such as Kuala Lumpur International Airport, Putrajaya district and UTP (Universiti Teknologi PETRONAS).

However, electric chiller's performance will be degraded after years' running, although regular maintenances have been conducted. It's a challenge for plant operator to accurately find out chiller's performance bottleneck and conduct effective maintenance, because there are many possible constraints which may impact chiller's performance, for example, ambient temperature, cooling demand and chiller compressor's electricity consumption.

The present paper studies electric chiller's performance bottleneck diagnosis method at UTP's district cooling plant. The method is an extension of RCA (Root Cause Analysis) diagnosis technology, which is originally designed for steam absorption chiller anomaly detection [2][3].

Figure 1 is the diagram of UTP district cooling system. UTP cooling plant supplies cooling water for the campus located at Bandar Seri Iskandar, Perak, Malaysia, which has students' population of 6,000 fully residential and total built-up area of 92,600 square meters. Between cooling plant and consumer buildings, HEX station is deployed to exchange heat between primary pipeline (linked to cooling plant) and secondary pipeline (linked to academic complex).

UTP cooling plant is a cogeneration plant, supplies not only cooling water, but also electricity. The major equipment in the plant is given as following:

- GAS Turbine: 4.2 MW x 2 unit
- Heat Recovery Steam Generator: 12,000 kg/hr x 2 unit
- Steam Absorption Chiller: 1250 RT x 2 unit
- Electric Chiller: 325 RT x 4 unit
- Thermal Energy Storage (TES): 10,000 RT

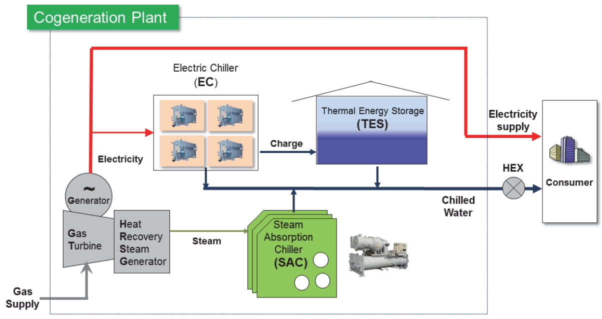

Fig. 1. UTP district cooling system diagram

In UTP plant, the operation schedule for cooling water production and supply can be described as following.

- During off-peak hours (from 7pm to 7am of next day), cooling demand from campus becomes low gradually, so steam absorption chillers are switched off after 11 pm, while electric chillers are started to produce chilled water for charging TES and supplying campus.

  Chilled_Water_Production = Chilled_Water_to_Campus + Chilled_Water_Charge_to_TES

- During peak hours (from 7am to 7pm), cooling demand becomes high, so TES discharges chilled water to campus, and steam absorption chiller produces chilled water for campus supply. While electric chillers are turned off due to high electricity requirement by the campus and limited electricity generation capability in the plant; unless TES and steam absorption chillers are not able to meet campus demand, electric chiller will be operated to produce chilled water.

  Chilled_Water_to_Campus = Chilled_Water_Production + Chilled_Water_Discharge_from_TES

Such operation schedule achieves energy optimization and saves operation cost, because it shifts electric chillers' electricity consumption from peak hours in the daytime to off-peak hours in the evening, which effectively reduces electricity requirement during peak hours.

As mentioned above, electric chillers function as a key role in UTP cooling plant for energy efficient operation; the present paper studies electric chillers' performance bottleneck diagnosis method by analyzing the plant data and adapting RCA method.

II. Related Work

There exist a large number of chiller plant fault detection and diagnosis researches.

[4~6] give extensive review on early study of chiller's anomaly detection and fault cause diagnosis. The rule-based fault diagnosis method is popular in fault detection and diagnosis research. Rules are usually developed from expert knowledge, theoretical principles, or historical data. In the rule based reasoning, a fault is diagnosed as soon as the corresponding rule is satisfied.

[7] proposes an intelligent chiller fault detection and diagnosis methodology using Bayesian belief network. It is effective in diagnosing faults based on uncertain, incomplete and conflicting information of measurements, expert knowledge, fault patterns, symptoms, etc.

[8] studies electric chillers' performances for campus cooling based on data from 2005 to 2011. The analysis identifies electric chillers' performances anomaly of lower COP (Coefficient of Performance) than normal range [4.2, 6.1], but was not able to quantitatively recognize root cause for performance degradation.

[9] and [10] propose some methods to detect performance bottleneck by using Principal Component Analysis (PCA) and Independent Component Analysis (ICA), but their work is limited to non-linear factors, such as control valves with excessive static friction, oscillating and sensor faults.

[2] develops a linear bottleneck analysis method RCA based on theory of constraint [11], it can detect performance deterioration factors such as equipment corrosion, but is limited to steam absorption chiller diagnosis.

The present paper adapts RCA based diagnosis method to electric chiller at UTP plant by defining electric chiller performance bottleneck model and bottleneck diagnosis method.

III. Electric Chiller Bottleneck Diagnosis

This section studies RCA diagnosis method extension for electric chillers in UTP plant, including performance definitions, performance - constraints correlation analysis, bottleneck models and diagnosis methods design.

A. Electric chiller performance definition

In UTP plant, electric chillers are air cooled chillers from Dunham Bush. Their performances are measured by CHW (CHilled Water supply or cooling load) and COP, defined as following.

$$CHW\ (RT) = 4200 * flow\_rate\ (m^3/hour) * (CHWr - CHWs)\ (degC) / 12661 \quad (1)$$

- CHWr: Chilled Water Return Temperature (degC);
- CHWs: Chilled Water Supply Temperature (degC);

$$COP = CHW\ (RT) / electricity\ consumption\ (KW) \quad (2)$$

B. Performance constraints analysis

In order to build electric chiller performance bottleneck model, the correlation between chiller performance and their constraints is studied by using UTP plant data. The chiller performance constraints include chiller electricity consumption, campus cooling demand, chiller cooling load and ambient air temperature.

1) Electricity consumption analysis.

For electric chiller, electricity is the major power source to produce chilled water. In theory, electric chiller's electricity consumption (majorly by compressor) should be in positive correlation with CHW performance: the more electricity is consumed, the more chilled water can be supplied.

We studied a typical electric chiller's CHW performance and its electricity consumption (ELE) during 24 hours at UTP plant, as shown in Fig. 2.

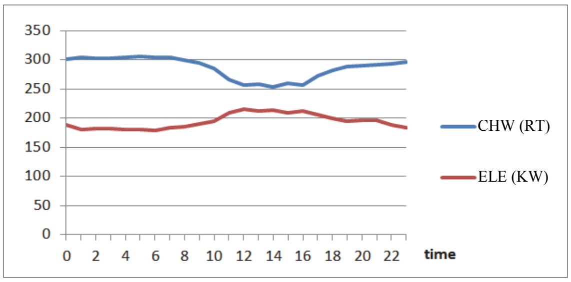

Fig. 2. Electric chiller's CHW and electricity

It is beyond the expectation that a negative correlation between CHW and ELE is observed in upper chart of Fig. 2. From 0h to 8h, CHW was high, while electricity was low; from 8h to 18h, CHW became low, and ELE was high; from 18h to 23h, CHW increased, while ELE decreased.

By analyzing electric chiller's COP performance, we found that COP was not fixed during a day: it's high in the evening and low during the daytime. High COP makes high CHW with less electricity during the evening, while low COP makes low

CHW with more electricity during the daytime. So it's COP's change that affects the correlation between CHW and ELE. We will further study the reason of electric chiller's COP change in section 4).

2) Cooling demand analysis

Cooling demand is another major constraint to CHW performance. At UTP plant, cooling demand is represented by CHWr (chilled water temperature returned from campus building). When cooling demand goes up and CHWr gets higher, electric chiller's evaporator will exchange more heat with returned chilled water, because temperature difference between evaporator and CHWr is enlarged, and as a result more cooling water (CHW) will be produced.

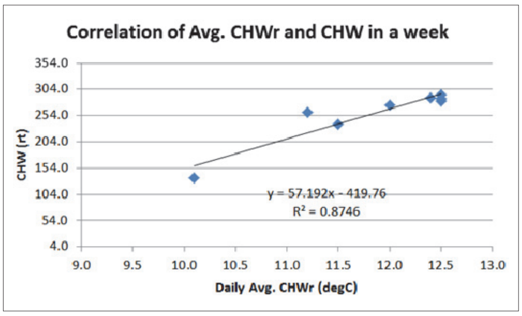

Fig. 3. Correlation of CHW and cooling demand (CHWr)

Figure 3 presents correlation of an electric chiller's CHW performance and cooling demand represented by CHWr. An electric chiller's one week data is analyzed, and a positive linear correlation with R^2 value of 0.87 is observed.

3) Cooling load analysis

According to Equation 2, electric chiller's cooling load (also represented as CHW) is a constraint of COP performance. When electricity consumption is fixed, the higher the CHW is, the higher the COP will be.

Figure 4 illustrates the positive linear correlation between electric chiller's COP and CHW, in which one trend line is observed during evening for TES charging and the other trend line is observed during daytime for direct cooling water supply to campus.

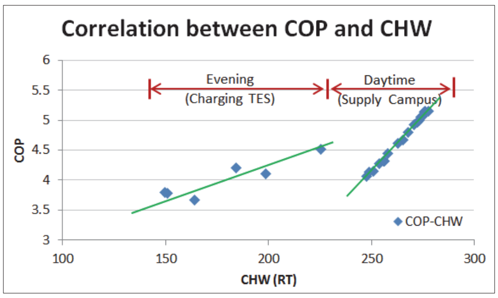

Fig. 4. Correlation between COP and CHW

4) Ambient temperature analysis

Ambient temperature is another key constraint to both CHW and COP performance, because at UTP plant, air fan is used to exchange heat with electric chiller's condenser instead of cooling water from cooling tower. When ambient air temperature gets high, the heat rejected by air fan and the condenser becomes low, so chilled water produced by electric chiller will be reduced. In order to maintain chilled water supply level, electric chiller's compressor has to work harder to raise temperature of refrigerant to enter condenser, which causes more electricity consumption and lower COP performance.

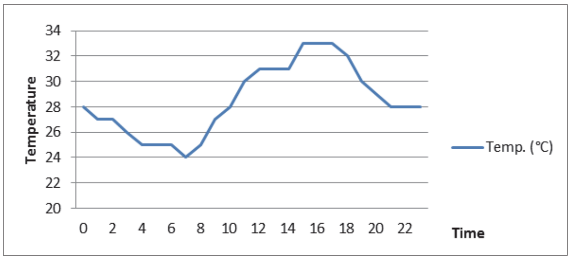

Fig. 5. Ambient temperature during a day at Ipoh, Malaysia

Figure 5 shows ambient temperature changes during a day, the data is from nearby weather station at Ipoh airport. Even though in tropical area, the temperature difference between daytime and night still was 8 degC, which is big enough to affect chiller's performance.

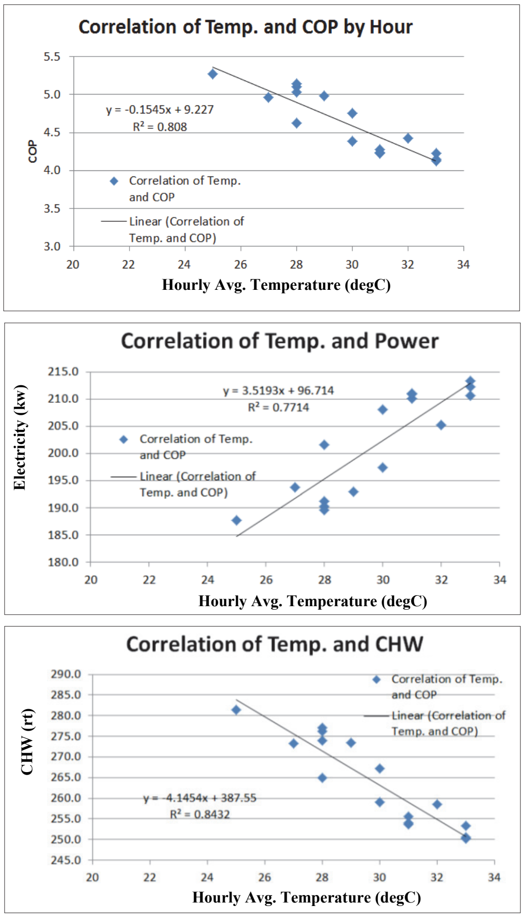

Fig. 6. Ambient temperature correlation with COP, CHW and electricity

Figure 6 shows ambient temperature correlation with COP, CHW and electricity consumption for a typical electric chiller at UTP plant based on hourly data. The results prove that ambient temperature could positively impact power consumption (electricity), and negatively impact CHW and COP performance.

C. Performance bottleneck analysis method

Based on above performance constrains analysis, we extend RCA method and build electric chiller's CHW performance bottleneck models in Equation 3, in which CHW performance is majorly impacted by constraints of electricity consumption (ELE), ambient air temperature (TMP) and cooling demand (CHWr).

$$CHW(i,t) = C_R(i,t) * CHWr(i,t) + C_T(i,t) * TMP(t) + C_E(i,t) * ELE(i,t) \quad i = 1..n \tag{3}$$

Where,

- $i = 1..n$, means one of the chillers in the plant.
- $CHW(i, t)$ is chiller i's chilled water output at time t, can be calculated from chilled water flow rate and chilled water temperature difference.
- $CHWr(i, t)$ is chilled water returned temperature for the chiller i at time t, representing cooling demand.
- $TMP(t)$ is ambient air temperature at time t.
- $ELE(i, t)$ is chiller i's electricity consumption at time t.
- $C_R(i, t)$ is correlation coefficient between $CHWr(i, t)$ and $CHW(i, t)$ at time t, which can be derived from linear regression analysis introduced in [2].
- $C_T(i, t)$ is correlation coefficient between $TMP(t)$ and $CHW(i, t)$ at time t, which can be derived from linear regression analysis introduced in [2].
- $C_E(i, t)$ is correlation coefficient between $ELE(i, t)$ and $CHW(i, t)$ at time t, which can be derived from linear regression analysis introduced in [2].

In Equation 3, performance constraints may impact CHW performance in different ways. For example, low ELE could lower performance of electric chiller's compressor; high TMP can lower cooling fan efficiency to reject heat from electric chiller's condenser; low CHWr could reduce heat exchange between chilled water and electric chiller's evaporator.

Each constraint's contribution ratio to the CHW performance can be calculated as following.

$$R_E(i,t) = |C_E(i,t) * ELE(i,t)| / P(i,t), \quad i = 1..n \tag{4}$$

$$R_R(i,t) = |C_R(i,t) * CHWr(i,t)| / P(i,t), \quad i = 1..n \tag{5}$$

$$R_T(i,t) = |C_T(i,t) * TMP(t)| / P(i,t), \quad i = 1..n \tag{6}$$

Where,

- $R_E(i, t)$ is chiller i's electricity consumption contribution ratio to CHW at time t;
- $R_R(i, t)$ is chiller i's returned chilled water temperature contribution ratio to CHW at time t;
- $R_T(i, t)$ is chiller i's ambient air temperature contribution ratio to CHW at time t;
- $P(i, t)$ is absolute summation of chiller i's all CHW constraints' contribution at time t, as defined in the following.

$$P(i,t) = |C_E(i,t) * ELE(i,t)| + |C_R(i,t) * CHWr(i,t)| + |C_T(i,t) * TMP(t)| \quad i = 1..n \tag{7}$$

Here we define a bottleneck as the constraint with the highest contribution at the moment. High contribution ratio of the constraint indicates high probability of the constraint to be the bottleneck of the chiller. For chiller i, if model's electricity consumption contribution ratio $R_E(i, t)$ is much greater than other constraints' contribution ratio, i.e. $R_R(i, t)$ and $R_T(i, t)$, then electricity consumption is considered as chiller i's CHW performance bottleneck at time t, and plant operator is suggested to check and adjust electricity supply as most effective operation for meeting chiller i's CHW target.

Similarly, according to COP performance definition (Equation 2) and constraints analysis, we define electric chiller's COP performance bottleneck model as following.

$$COP(i,t) = C'_C(i,t) * CHW(i,t) + C'_T(i,t) * TMP(t) + C'_E(i,t) * ELE(i,t) \quad i = 1..n \tag{8}$$

Where,

- Some parameters have already defined in Equation 3, except for the following.
- $COP(i, t)$ is chiller i's COP performance at time t.
- $C'_C(i, t)$ is correlation coefficient between $CHW(i, t)$ and $COP(i, t)$ at time t, which can be derived from linear regression analysis introduced in [2].
- $C'_T(i, t)$ is correlation coefficient between $TMP(t)$ and $COP(i, t)$ at time t, which can be derived from linear regression analysis introduced in [2].
- $C'_E(i, t)$ is correlation coefficient between $ELE(i, t)$ and $COP(i, t)$ at time t, which can be derived from linear regression analysis introduced in [2].

COP performance constraints' contribution ratios are defined as following.

$$R'_E(i,t) = |C'_E(i,t) * ELE(i,t)| / P'(i,t), \quad i = 1..n \tag{9}$$

$$R'_C(i,t) = |C'_C(i,t) * CHW(i,t)| / P'(i,t), \quad i = 1..n \tag{10}$$

$$R'_T(i,t) = |C'_T(i,t) * TMP(t)| / P'(i,t), \quad i = 1..n \tag{11}$$

Where,

- $R'_E(i, t)$ is chiller i's electricity consumption contribution ratio to COP at time t;
- $R'_C(i, t)$ is chiller i's cooling load contribution ratio to COP at time t;

- $R'_T(i, t)$ is chiller i's ambient air temperature contribution ratio to COP at time t;
- $P'(i, t)$ is absolute summation of chiller i's all COP constraints' contribution at time t, as defined in the following.

$$P'(i,t) = |C'_E(i,t) * ELE(i,t)| + |C'_C(i,t) * CHW(i,t)| + |C'_T(i,t) * TMP(t)| \quad i = 1..n \tag{12}$$

It's similar to CHW bottleneck diagnosis that high COP contribution ratio of the constraint indicates its high probability to be COP bottleneck, and specific check and maintenance should be given to the bottleneck constraint.

IV. Analysis Result

Based on the electric chiller performance models established in section III, we use two years' sensor data of UTP plant to analyze electric chiller's CHW and COP performance bottleneck from 2014 to 2015.

A. CHW performance analysis

Firstly, we analyze a typical electric chiller's CHW performance bottleneck in Fig. 7. There are four areas from top to bottom: CHW performance area, normalized constraint sensor data, bottleneck contribution ratio area and bottleneck display bar. Bottleneck display bar shows bottleneck diagnosis result; different bottleneck is represented in different color.

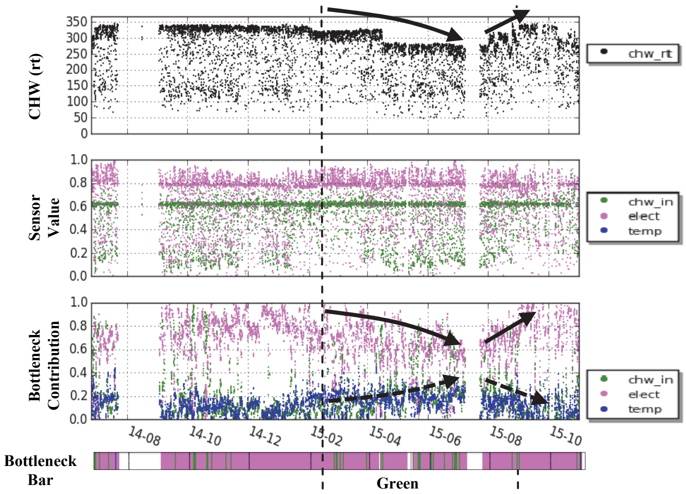

Fig. 7. RCA analysis for electric chiller's CHW performance bottleneck

In Fig. 7, the electric chiller's CHW bottleneck is dominated by electric power supply or consumption, because in bottleneck contribution area, the electric chiller's power consumption contribution ratio (elect) is always higher than other constraints such as ambient temperature (temp) and cooling demand represented by returned chilled water temperature (chw_in), which makes most area in bottleneck bar display in pink color.

But from Feb 2015 to Jul 2015, CHW performance slowly deteriorates from 325 rt to 275 rt. During the same period, in bottleneck contribution area, electricity contribution rate (in pink color) is obviously lowered, while cooling demand's contribution (in green color) goes up and results in more green color on bottleneck bar, which suggests cooling demand is the root cause for CHW deterioration.

Based on root cause analysis result, we can further give out plant maintenance suggestion. Considering UTP actual situation and maintenance history, there are two possible reasons to make cooling demand become bottleneck: one is weather condition, and the other is HEX station anomaly. Firstly, lower weather temperature may lower cooling demand, but in 6 months' of CHW deterioration, monthly average temperature change at UTP/Ipoh district is less than 2 degrees Celsius, which is too small and impossible to continuously pull down cooling demand in 6 months. Then, HEX station is suggested as maintenance target for recovering cooling demand, because HEX station exchanges heat between cooling plant's primary pipe and campus buildings' secondary pipeline, and the deterioration of exchange efficiency at HEX can lower returned chilled water temperature or cooling demand to cooling plant. The root cause analysis and diagnosis process is proven effective by HEX maintenance log: one of two heat exchangers at HEX station was found faulty and maintained in August 2015, after that cooling demand and CHW performance is effectively recovered as shown in Fig. 7.

B. COP performance analysis

Regarding electric chiller's COP performance, we analyze its bottleneck in similar way to CHW analysis.

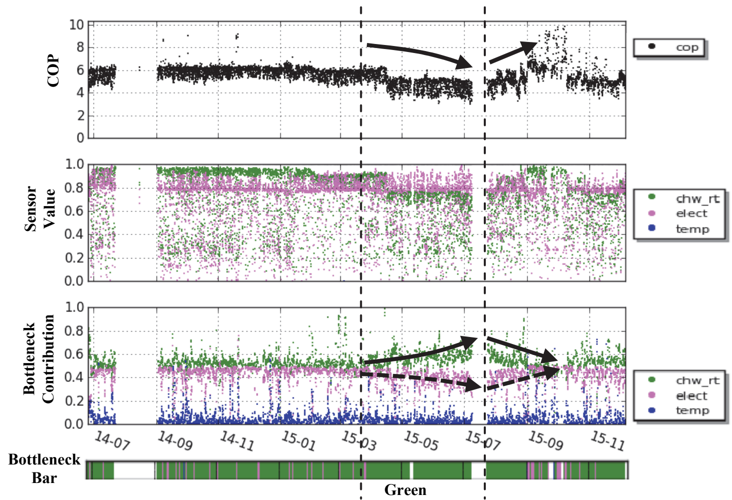

Fig. 8. RCA analysis for electric chiller's COP performance bottleneck

Figure 8 shows COP performance bottleneck analysis result for the same electric chiller as in Fig. 7. Bottleneck display bar is mostly in green color, showing cooling load (chw_rt) is diagnosed as main bottleneck for the chiller's COP. This is because bottleneck contribution rate of cooling load is always higher than other constraints such as ambient temperature (temp) and electricity consumption (elect).

From Mar 2015 to Jul 2015, an anomaly is observed in which COP performance drops from around 5.5 to 4.5. The root cause is diagnosed as cooling load decreasing, because cooling load's contribution ratio rises to 0.6, which is higher than its usual value 0.5, and also higher than other constraint sensors' contribution ratio. Combining with CHW bottleneck analysis for the same chiller (in Fig. 7), which already diagnosed cooling demand as root cause of the chiller's CHW (equivalent to cooling load), we can derive that cooling demand is the deepest root cause for COP performance drop. Therefore, the same maintenance suggestion as CHW analysis is made that requires HEX station check. The COP bottleneck analysis and root cause diagnosis mentioned above is verified by actual HEX station maintenance in August 2015, which recovers chiller's COP to around 6 in following month, as shown in Fig. 8.

V. CONCLUSION

The paper studies electric chiller's performance bottleneck diagnosis using RCA analysis at UTP district cooling plant. Through RCA adaption, two electric chiller performance bottleneck models for CHW and COP are developed. In the case study, a performance anomaly caused by cooling demand drop is diagnosed and verified by maintenance at UTP HEX station. However, in order to apply RCA to whole cooling plant for early anomaly detection and diagnosis, more model adaptation and case studies for larger and hybrid cooling plants are needed.

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