

# An Empirical Study on Performance Optimization at District Cooling Plant of Universiti Teknologi PETRONAS

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**Abstract**—District cooling plant has been widely used in comfort cooling service (for airport, university, shopping mall, etc.) and industry process cooling service. However, current district cooling plants are becoming more complex with hybrid cooling equipment such as Steam Absorption Chiller, Electric Chiller, Thermal Energy Storage, etc., it's challenging to implement energy efficient cooling operation with high cooling performance and low energy consumption. Conventional optimization uses cost objective function to calculate energy consumption with operation scheduling variables as input. Through searching variables' space, the variable set with minimum energy cost is selected as optimal operation solution. However, this method is not valid when correlation between power consumption and scheduling variable is weak. The present paper enhances operation scheduling optimization by integrating RCA (Root Cause Analysis) method to identify the occasion when the required correlation is strong and optimization objective function can be applied. Also, the proposed method can integrate with empirical performance knowledge to solve local optimization problem. The experiments at district cooling plant of UTP (*Universiti Teknologi PETRONAS*) shows new operation scheduling optimization can save power by 50% averagely.

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

## I. INTRODUCTION

District cooling plant has been widely used for comfort cooling service in commercial districts (e.g. airport, university, shopping mall, etc.) and industry process cooling service. Currently, district cooling plants are becoming more complex with many hybrid cooling equipment such as Steam Absorption Chiller (SAC), Electric Chiller (EC), Thermal Energy Storage (TES), etc., which makes it quite challenging to implement energy efficient cooling operation with high cooling performance and minimal energy consumption [1].

The present paper studies performance optimization at district cooling plant of UTP (*Universiti Teknologi PETRONAS*) (Fig. 1), which is located in Bandar Seri

Iskandar, Malaysia, having students' population of 5,657 fully residential and total built-up area of 92,600 square meters.

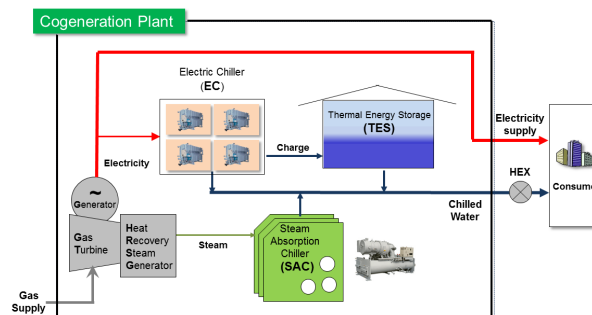


Fig. 1. District cooling plant at UTP (*Universiti Teknologi PETRONAS*)

UTP plant is a hybrid cogeneration system, supplies not only cooling water, but also electricity. The plant's main equipment includes:

- GAS Turbine: 4.2 MW x 2 unit
- Heat Recovery Steam Generator: 12,000 kg/hr x 2 unit
- SAC: 1250 RT x 2 unit
- EC: 325 RT x 4 unit
- TES: 10,000 RTh

In cooling water generation and supply, UTP plant takes a two-stage operation schedule: TES charging stage and discharging stage.

- TES charging stage: from 5:30 pm to 6:30 am of next day, campus cooling demand is at off-peak period, so SACs with bigger cooling capacity are switched off, while ECs with smaller cooling capacity starts to produce chilled water for charging TES and supplying campus.
- TES discharging stage: Normally from 7am to 5pm, cooling demand stays at peak period, so TES and

SACs start to discharge or produce chilled water for campus, while ECs are turned off to increase electricity supply capability. In case TES and SACs are not able to meet campus demand, ECs will be scheduled to supply chilled water for campus.

In order to optimize this hybrid cooling system operation to minimize energy consumption, at first we need to estimate the problem complexity. In UTP plant, basic cooling equipment are 2 SACs, 4 ECs and 1 TES. If the operation scheduling is conducted hourly and cooling load adjustment step is 1% of equipment capacity, then total number of plant scheduling candidates will be  $1.07 \times 10^{14}$  within one hour, as calculated in the following.

- For each equipment:  
Cooling load scope = [0%, 1%, ... , 100%]  
Num of scheduling candidates = 101
- For the whole cooling system:  
Num of scheduling candidates for 2 SACs =  $101^2$   
Num of scheduling candidates for 4 ECs =  $101^4$   
Num of scheduling candidates for 1 TES = 101  
Num of total scheduling candidates =  $101^{2+4+1} = 1.07 \times 10^{14}$

If the energy consumption evaluation time for a scheduling candidate is 0.3ms, then total time to find optimal schedule is 372,269 days ( $= 1.07 \times 10^{14} \times 0.3\text{ms}$ ). So, UTP cooling system operation optimization actually is a computing explosion problem. Conventional solution for such problem is to reduce search space through some local optimization algorithms, which seeks local minimum cost values, not global optimal values.

The present paper studies the cooling operation optimization by applying conventional local optimization solver on energy cost objective function for the process of TES charging. Two issues are identified in the study: 1) invalidity of objective function; and 2) wide searching space, resulting in inaccurate solution due to local minimum problem. Therefore, the paper proposes an enhanced optimization method by integrating RCA (Root Cause Analysis) and verifies the new method effectiveness through experiments at UTP plant.

## II. RELATED WORK

[2] proposes a chillers' operation optimization method to improve energy efficiency based on RCA (Root Cause Analysis). It can detect the plant performance bottleneck, and choose suitable operation to solve the bottleneck, thus improve total plant performance. The limitation of the method is it only applies on SAC, and energy saving is only for steam energy.

[3] extends RCA method from SAC to EC, however the method only applies on anomaly diagnosis, not performance or operation optimization.

[4] and [5] suggest that sequencing multiple chillers by allowing the chillers with high COP (Coefficient of

Performance) to be operated at full load can improve the plant overall performance or energy efficiency.

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

Where

$$CHW = Chilled\ Water\ Supply\ Capacity$$

However, in real practice, some chillers achieve their highest COP at 70% ~ 80% of design load capacity; higher or full load actually makes them sub-optimal. Moreover, COP shouldn't be regarded as only factor to decide operation scheduling priority, because COP represents a correlation between CHW and electricity consumption, while this correlation is not established when some other factors such as ambient temperature becomes CHW performance bottleneck and dominates CHW variation.

[6] studies the operation optimization for a combination of absorption and compression chillers in a trigeneration plant. Through curve-fitting to supplier's data, the chillers' operation optimization objective function is built. Simulation shows the optimization can determine each chiller's working load for maximizing operating cost (or carbon emission) saving.

In sum, most researches of chillers' operation scheduling rely on conventional optimization, while some of others prefer to utilize new promising approach such as RCA based method. The present paper will evaluate effectiveness of conventional optimization approach by applying on UTP plant, then try to identify the problem and study the potential solution through integrating RCA method.

## III. OPERATION SCHEDULING OPTIMIZATION

This section will build cost objective function for chillers' operation scheduling optimization through conventional approach, and examine its shortcomings.

To reduce the computation complexity and time, only TES charging scheduling from 0 am to 5 am at UTP cooling plant is optimized. The scheduling variables are cooling load of 4 air cooled ECs from Dunham Bush, and optimization objective function is to minimize ECs' power consumption while meeting the total cooling water requirement for charging TES.

Chillers' scheduling optimization objective function is defined as following.

$$Z = \sum_i X_i \tag{1}$$

$$X_i = E_i(x_i) \tag{2}$$

Where

- $i = \{1, 2, 3, 4\}$ , referring to four ECs: EC\_A, EC\_B, EC\_C and EC\_D.
- $Z$  = total electricity consumption of all chillers.
- $X_i$  = the  $i^{\text{th}}$  chiller's electricity consumption.
- $x_i$  = the  $i^{\text{th}}$  chiller's scheduling variables, representing the chiller's cooling load with percentage of design capacity.

- $E_i$  = the correlation function between scheduling variable  $x_i$  and electricity consumption  $X_i$ .
- $\sum_i (x_i * l_i) \leq L$ .  $L$  is total cooling water for charging TES;  $l_i$  is the  $i^{\text{th}}$  chiller's design capacity. In present paper, all 4 chillers have same design capacity, which is 325 RT.

Chiller's electricity consumption function  $E_i$  is built through polynomial regression method and historical data. For EC, electricity is the major power source to produce chilled water. In theory, EC's electricity consumption should be in positive correlation with CHW performance: the more electricity is consumed, the more chilled water can be supplied. However, in actual chiller operation, it's not always established. Fig. 2 shows a negative correlation between CHW and ELE (electricity consumption) during 24 hours at UTP plant, which means some other factors have stronger correlation with electricity than CHW.

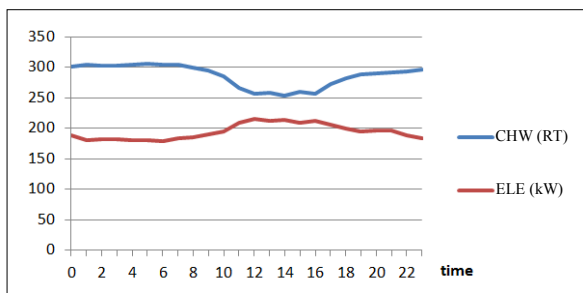


Fig. 2. EC's CHW and electricity

Further study shows that ambient temperature is another key constraint to chiller's electricity consumption, because air fan is used to exchange heat with EC's condenser. When ambient air temperature gets high, the heat rejected by air fan from the condenser becomes low, so chilled water produced by EC will be reduced. In order to maintain chilled water supply level, EC's compressor has to work harder to raise temperature and pressure of refrigerant to enter condenser, which causes more electricity consumption. Fig. 3 shows ambient temperature correlation with electricity consumption for a typical EC at UTP plant based on hourly data. The results prove that ambient temperature could positively impact power consumption (electricity).

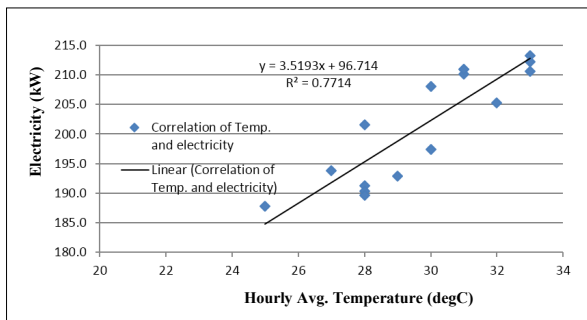


Fig. 3. Ambient temperature correlation with electricity

Besides ambient temperature, fan rotation speed has similar impact on chiller's electricity. Therefore, the correlation function  $E_i$  between scheduling variable  $x_i$  (representing CHW, or cooling load) and electricity consumption  $X_i$  is not always established, which becomes a major limitation when applying conventional scheduling optimization method on practical cooling plant.

#### IV. IMPROVEMENT ON SCHEDULING OPTIMIZATION BY RCA

To solve the limitation in current optimization solution, the present paper introduces RCA method to determine the valid occasion for applying correlation function between CHW and electricity.

RCA method can be used to analyze ECs' performance constrains correlation and bottleneck, including CHW, electricity consumption (ELE), ambient air temperature (TMP) and cooling demand (CHWr) [3].

According to RCA method, EC's performance bottleneck model is defined in (3).

$$CHW(i,t) = C_R(i,t) * CHWr(i,t) + C_T(i,t) * TMP(t) + C_E(i,t) * ELE(i,t) \quad (3)$$

Where

- $i = 1..n$ , means one of the chillers in the plant,  $n=4$ .
- $CHW(i, t)$  is chiller  $i$ 's chilled water output at time  $t$ , calculated by water flow rate & 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  $t$ , derived from linear regression analysis in [3].
- $C_T(i, t)$  is correlation coefficient between  $TMP(t)$  and  $CHW(i, t)$  at time  $t$ , derived from linear regression analysis in [3].
- $C_E(i, t)$  is correlation coefficient between  $ELE(i, t)$  and  $CHW(i, t)$  at time  $t$ , derived from linear regression analysis in [3].

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

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

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

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

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

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 following.

$$P(i, t) = |C_E(i, t) * ELE(i, t)| + |C_R(i, t) * CHWR(i, t)| + |C_T(i, t) * TMP(t)| \quad (7)$$

RCA defines the 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 to improve chiller  $i$ 's CHW.

Through the RCA bottleneck analysis, we can determine the occasion when the correlation function  $E_i$  between CHW and electricity is valid and can be applied to scheduling optimization objective function.

The optimization objective function is updated by adding a coefficient  $c_i$  as following.

$$Z = \sum_i (c_i * X_i), \quad i = \{1, 2, 3, 4\} \quad (8)$$

Where

- $c_i$  = objective function coefficient, indicating if the objective function is valid for the  $i^{\text{th}}$  chiller.
- $c_i = 0$ , if chiller  $i$ 's CHW bottleneck is not electricity.
- $c_i = 1$ , if chiller  $i$ 's CHW bottleneck is electricity.

If electricity is identified as the bottleneck of chiller's CHW performance, it means electricity has much stronger correlation with CHW than other constraints at current moment, so correlation function  $E_i$  between CHW and electricity is valid and coefficient of  $c_i$  in objective function is assigned as "1". Otherwise, the correlation between electricity and CHW is very weak, chiller's CHW or cooling load scheduling has not much impact on electricity consumption, so the coefficient of  $c_i$  in objective function is assigned as "0". How to schedule the chillers with weak correlation between power cost and cooling load is beyond the paper's discussion.

## V. EXPERIMENT

This section evaluates new operation optimization approach established in section IV, by using two years' sensor data of UTP plant from 2014 to 2015.

Firstly, a 6 hours' TES charging operation is selected for optimization. The original scheduling from 0 am to 5 am is shown in Table I, in which only EC\_C is manually scheduled by plant operator to produce chilled water and charge TES. Total cooling water for charging  $L$  is 849 RT, and total electricity consumption  $Z$  is 1328 kW.

TABLE I ORIGINAL CHARGING OPERATION SCHEDULING

*** Original Charging During [0h:5h] ***						
Hour	EC_A	EC_B	EC_C	EC_D	CHW (RT)	Elec (KW)
[ 0 ]	0.0%	0.0%	56.6%	0.0%	184.0	234.0
[ 1 ]	0.0%	0.0%	46.5%	0.0%	151.0	227.0
[ 2 ]	0.0%	0.0%	41.8%	0.0%	136.0	217.0
[ 3 ]	0.0%	0.0%	41.2%	0.0%	134.0	216.0
[ 4 ]	0.0%	0.0%	37.5%	0.0%	122.0	216.0
[ 5 ]	0.0%	0.0%	38.5%	0.0%	125.0	218.0

Fig. 4 shows EC\_C's CHW performance bottleneck analysis by applying RCA method on 2 years' data. 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.

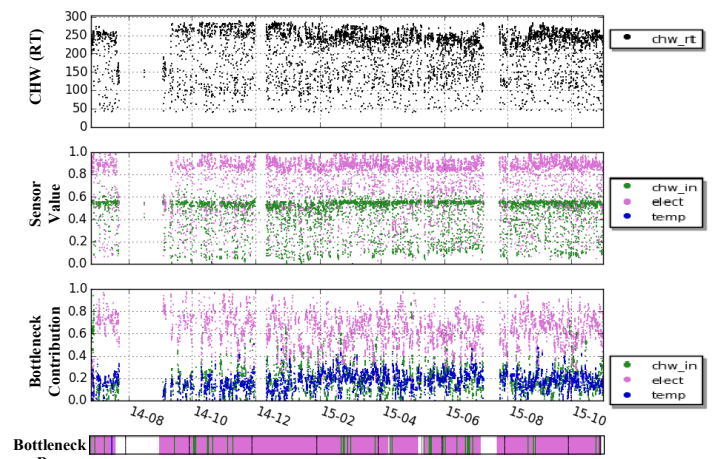


Fig. 4. RCA analysis for EC's CHW performance bottleneck

During most of the time, EC\_C's CHW bottleneck is dominated by electricity consumption, because in bottleneck contribution area, the contribution ratio of EC's power consumption (elect) is always higher than other constraints such as ambient temperature (temp) and returned chilled water temperature (chw\_in), which makes most area in bottleneck bar display in pink color.

In the present scheduling optimization, only one week's CHW bottleneck diagnosis result before scheduling time is used to check the correlation validity. For EC\_C, the bottleneck analysis result in a week before scheduling time indicates the correlation between electricity and CHW is valid and strong.

Therefore, Fig. 5 builds a correlation function  $E_i$  for EC\_C through polynomial regression method and historical data in a week before scheduling time.  $R^2$  of 0.8954 suggests correlation function is well established to match observations.

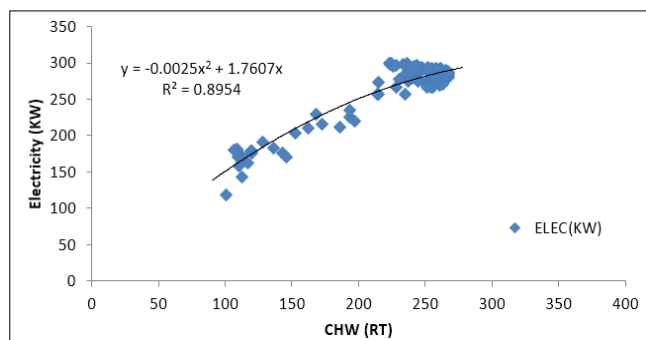


Fig. 5. Correlation between electricity and CHW

Due to validity of EC\_C's correlation function  $E_i$ , the optimization objective function is updated as following.

$$Z = c_1 * E_1(x_1) + c_2 * E_2(x_2) + c_3 * E_3(x_3) + c_4 * E_4(x_4) \quad (9)$$

Where

- $c_3 = 1$
- $E_3(x_3) = -0.0025 * (x_3 * 325)^2 + 1.7607 * x_3 * 325$

Similarly, optimization objective function  $Z$  can be updated according to the validity of other chillers' correlation functions, which are defined as following.

$$\begin{aligned} \text{EC\_A: } E_1(x_1) &= 0.0012 * (x_1 * 325)^2 + 0.1939 * x_1 * 325 \\ \text{EC\_B: } E_2(x_2) &= -0.0031 * (x_2 * 325)^2 + 1.782 * x_2 * 325 \\ \text{EC\_D: } E_4(x_4) &= -0.0038 * (x_4 * 325)^2 + 2.1879 * x_4 * 325 \end{aligned}$$

In order to implement optimization, the present paper chooses a general nonlinear optimization solver – SOLNP as a solver [7][8].

In the 1<sup>st</sup> experiment, we assume EC\_A's, EC\_B's and EC\_C's CHW bottlenecks are electricity except for EC\_D, although there are many other possible combinations which are subject to actual CHW bottleneck analysis during plant operation. So, the validity of chillers' objective functions are represented as following coefficients.

$$c_1 = 1, c_2 = 1, c_3 = 1, c_4 = 0$$

Table II shows TES charging optimization result after applying SOLNP, which saves electricity by 21% through distributing cooling load on EC\_A, EC\_B and EC\_C.

TABLE II CHARGING OPERATION SCHEDULING OPTIMIZATION CASE 1

*** Optimal Charging During [0h:5h] ***						
Hour	EC_A	EC_B	EC_C	EC_D	CHW (RT)	Elec (KW)
[ 0 ]	0.0%	0.0%	0.0%	0.0%	0.0	0.0
[ 1 ]	0.0%	0.0%	0.0%	0.0%	0.0	0.0
[ 2 ]	57.3%	59.9%	0.0%	0.0%	380.9	300.2
[ 3 ]	33.4%	0.0%	60.1%	0.0%	303.8	296.2
[ 4 ]	55.0%	45.9%	0.0%	0.0%	328.0	272.5
[ 5 ]	0.0%	44.7%	0.0%	0.0%	145.4	185.3

However, current solution is probably not the most optimal due to SOLNP's local minimum problem. Based on empirical

knowledge, EC\_A may deliver higher performance than the other chillers if giving high cooling load, e.g., greater than 55%. So, a 2<sup>nd</sup> experiment is designed. We assume EC\_A's CHW bottleneck is electricity from 0 am to 5 am, while EC\_B's and EC\_D's bottlenecks are not. In the objective function, the coefficients are updated as following.

$$c_1 = 1, c_2 = 0, c_3 = 0, c_4 = 0$$

By applying SOLNP on the objective function  $Z$ , the charging operation scheduling is optimized in Table III. Cooling load is shifted from EC\_B and EC\_C to EC\_A, and total chilled water production is 868 RT with electricity consumption of 404 kW, saving power by 70% (924 kW).

TABLE III CHARGING OPERATION SCHEDULING OPTIMIZATION CASE 2

*** Optimal Charging During [0h:5h] ***						
Hour	EC_A	EC_B	EC_C	EC_D	CHW (RT)	Elec (KW)
[ 0 ]	66.1%	0.0%	0.0%	0.0%	214.9	99.3
[ 1 ]	67.8%	0.0%	0.0%	0.0%	220.4	101.8
[ 2 ]	0.0%	0.0%	0.0%	0.0%	0.0	0.0
[ 3 ]	65.7%	0.0%	0.0%	0.0%	213.7	98.7
[ 4 ]	0.0%	0.0%	0.0%	0.0%	0.0	0.0
[ 5 ]	67.5%	0.0%	0.0%	0.0%	219.4	101.3

Comparing two experiments, the 1st has wider searching space, but fails to get most optimal scheduling because of optimizer's local minimum problem; while the 2nd has more limited searching space, but by utilizing empirical performance knowledge, it finds more energy-saving scheduling. The result suggests in practical operation the proposed optimization approach should be integrated with empirical knowledge to limit search space and get better optimal solution. Averagely, the proposed scheduling optimization implements electricity saving by 50% with randomly selected bottleneck combinations.

## VI. CONCLUSIONS

The paper studies ECs' operation scheduling optimization during TES charging process at UTP cooling plant. In order to solve the limitation of conventional optimization approach, RCA bottleneck detection method is integrated to determine the occasion when to apply power cost objective function. Also, the empirical knowledge is utilized to limit search space and avoid local optimization problem. The experiment and simulation shows the new approach can save electricity by 50% averagely.

However, the empirical knowledge has limitation in itself, which may give wrong direction for optimal solution searching under certain circumstances. Also, the inaccuracy of objective function is not completely removed, because other constraints still impact the electricity consumption even when CHW has stronger correlation with electricity.

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## REFERENCES

- [1] Energy Design Resources, "Design brief: chiller plant efficiency," <http://energydesignresources.com/resources>, 2015.
- [2] X.M. Zhang, A. Sato, Y. Kudo, J. Okitsu, T. Nakamura and M. A. Abd Majid, "Energy Efficient Operation Based on Root Cause Analysis for Multiple-chiller Plant," 5th IEEE International Conference on Control System, Computing and Engineering, Penang, Malaysia, 27-29 Nov, 2015
- [3] X.M. Zhang, A. Sato, Y. Kudo, T. Nakamura, J. Okitsu, H. Aoki and M. A. Abd Majid, "A Case Study of Electric Chiller Performance Bottleneck Diagnosis by Root Cause Analysis," IEEE International Conferences on Information Technology, Information Systems and Electrical Engineering (ICITISEE 2016), Yogyakarta, Indonesia, 23-24 Aug, 2016
- [4] M. Behl, T. X. Nghiem and R. Mangharam, "Green scheduling for energy-efficient operation of multiple chiller plants," IEEE real-time systems symposium, San Juan, 5-7 Dec. 2012, pp. 195-204.
- [5] CIBSE (Chartered Institution of Building Services Engineers), CIBSE Guide F: Energy Efficiency in Buildings, 2nd ed., 2004.
- [6] C. Underwood, B. Ng and F. Yik, "Scheduling of multiple chillers in trigeneration plants," *Energies*, Aug. 2015, pp. 11095-11119.
- [7] Alexios Ghalanos and Stefan Theussl, "R\_SOLNP: General Non-Linear Optimization," 2015-07-02.
- [8] Y.Ye, "Interior algorithms for linear, quadratic, and linearly constrained non linear programming," PhD Thesis, Department of EES Stanford University, Stanford CA, 1987.