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Optimal Operation of Chillers Plant in Academic Building by using Linear Programming Approach

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The operation of chillers plant in the HVAC system is not ideally efficient in major academic buildings because the chillers are operated without accounting for the cooling load demand of the air-conditioning area of the building. The current operation of the chillers plant may fall under two cooling effects, namely excessive cooling effect that will reduce the efficiency of the chillers and inadequate cooling effect that may create an unpleasant environment inside the air-conditioning area. This is because the cooling load demand of the air-conditioning area of the building is unknown and is not numerically measured. The main aim of this study is to find the optimal operation of chillers plant in HVAC system by formulating an optimization framework with the main goal of minimizing energy consumption and electricity costs. The formulation of the optimization framework for chillers plant operation is modelled as Linear Programming (LP) to establish real representation of the chillers plant. The energy consumption profile, cooling load demand, cooling capacity and COP can be obtained by using historical data analysis. The optimization framework is modelled in GAMS v38.2.1 and solved by CPLEX solver to obtain the optimum input for the chillers plant in the HVAC system. The minimum total power consumption can be achieved by optimally coordinating the operation of chillers, cooling towers and AHUs while maintaining room temperature. From the cost comparison analysis between the current and optimal chillers plant, considerable cost reduction is expected to be less than 5 % if the chillers plant is operating efficiently or greater than 30 % if the chillers plant is not functioning effectively. Therefore, this study is beneficial to the administration of academic building to find a strategic action plan to promote cost optimization in the operation of the chillers plant.

1. Introduction

Buildings are one of the primary electricity consumers that is accounting for up to 52 % of total electricity consumption, in comparison to 45 % by the industrial sector and 3 % by the other sector in 2017 (Energy Commission, 2017). The heating, ventilation, and air conditioning system (HVAC) contributes to a major fraction of electricity consumption in commercial buildings. A central chillers network that is commonly used in the HVAC system for providing sufficient cooling air for the buildings is the largest electricity consumer in the building. Therefore, energy management for the chillers network has become essential to investigate potential strategies for reducing power demand and improving the energy efficiency of the chillers.

The main operational performance of the chiller can be monitored by measuring the coefficient of performance (COP). COP is usually not uniform throughout the operation period due to differences in the sequencing control strategy of multiple chillers (Liu et al., 2017) and fluctuation in cooling load demands (Sala-Cardoso et al., 2019) that contribute to significant changes in power consumption profile. The performance of the chillers can be further improved by considering cooling load demands in the optimization approach to find the opportunity and the flexibility of chiller operation to reduce electrical power utilization (Shao et al., 2019). It is hard to predict the cooling load demands of the building because of inaccurate information at the design stage and limited operational data to predict system performance (Huang et al., 2018). The cooling load demands may vary in a

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large range depending on weather conditions and the number of occupants in the building. Since the operation of chiller plant is strongly dependent on the dynamic change of cooling load demand of the building, the current practice in the academic building by using the conventional scheduling method of manual control may not be accurate enough in commanding the HVAC to operate as efficiently as possible.

Optimization techniques can be adopted to find the best operation strategy for HVAC, especially for chillers which reflect the dynamic change of cooling load, energy efficiency, and energy cost without scarifying human thermal comfort (Varbanov et al. 2021). The majority literatures, neglected the impact of power change of the chiller system and instead concentrated primarily on the air-loop heat exchange from thermal zones (Wang et al., 2022). In this paper, integrated chiller-AHU plant, which consists of a cooling tower system, a chiller system, and air handling units are considered with time-varying air mixed temperature in the optimisation framework. The contribution of this study is the proposed optimization model is expected to represent the actual operation of the chillers plant by including important equations (e.g., energy consumption, cooling load, cooling tower effectiveness). The second contribution is the percentage of cost saving between the current and optimal chiller plant is known to further investigate its process flexibility and availability for reducing power demand.

2. Problem statement

The main focus of the optimization model for the operation of the chillers network is to find the best operating condition of the chillers plant considering the detailed operation of chillers, cooling tower, and air handling units for an academic building. The cooling supply and demand of the building are considered for the chiller units to operate based on the predicted cooling demand by the building space. A linear programming (LP) model is presented for the optimisation problem considered in this study. The optimisation problem of chillers network is formally defined according to the following characteristics: (i) a given time horizon of eight hours is divided into an equal length of an hour; (ii) a number of two chillers with the given minimum and maximum chiller's temperature (i.e., return and supply temperature of chilled water); (iii) a set of compressors in the chillers network; (iv) a number of thirteen AHUs with minimum and maximum air temperature. (i.e., return and supply air temperature); (v) a set of pumps to transfer the flow of chilled water to AHU and condenser water to the cooling tower, and (vi) a fixed tariff electricity price is introduced.

The main optimal results that need to be made by the optimization model for every time are: (i) the amount of cooling load of the chiller; (ii) the chilled water return and supply temperature for chillers; (iii) the hot air and cooled air supply temperature for AHU; (iv) the air mass flow rate for the cooling tower; (v) the cooling requirement of the building; (vi) the power consumption for each compressor in the chiller system; (vii) the heat rejection from the cooling tower. The main optimal results are achieved by formulating the overall optimization model of the chiller plant to minimise the electricity costs.

3. Optimisation framework

The operation of chiller network is modelled as Linear Programming (LP) model. The main part of the optimisation framework consists of: (i) constraints related to the chiller system, (ii) constraints related to the cooling tower, (iii) constraints related to AHU, and the (iv) objective function. The parameters and variables of the mathematical model are written as small letters for parameters and capital letters for variables.

3.1 Equations for chiller system

The chiller system consists of the evaporator, condenser, compressor and expansion valve. Eq(1) models the cooling capacity of the evaporator ($Q_{(i,t)}^{evap}$), and Eq(2) describes the heat transfer for the condenser ($Q_{(i,t)}^{cond}$). Eq(3) defines the power consumption of a chiller ($W_{(i,t)}^{chiller}$) that is closely related to the temperature difference of the evaporator based on study by Deng et al. (2015). Coefficients $\beta_{(i,t)}$ and $\gamma_{(i,t)}$ are obtained by regression analysis of actual measured chiller data (Theng et al., 2021).

$$Q_{(i,t)}^{evap} = \dot{m}_i^{chw} c_w \left(T_{(i,t)}^r - T_{(i,t)}^s\right) \qquad \forall i \in I, t \in T \tag{1}$$

$$Q_{(i,t)}^{cond} = Q_{(i,t)}^{evap} + W_{(i,t)}^{chiller} \qquad \forall i \in I, t \in T \tag{2}$$

$$W_{(i,t)}^{chiller} = \beta_{(i,t)}\left(T_{(i,t)}^r - T_{(i,t)}^s\right) + \gamma_{(i,t)} \quad \forall i \in I, t \in T \tag{3}$$

The chilled water return temperature ($T_{(i,t)}^r$) is modeled according to Eq(4) that are based on partial load ratio ($PLR_{(i,t)}$). PLR is the ratio of cooling capacity of the evaporator with the maximum cooling capacity based on Eq(5).

$$T^{r}_{(i,t)} = T^{s}_{(i,t)} \frac{PLR_{(i,t)} q^{max}_{c(i)}}{\dot{m}^{chw}_{i} c_{w}} \qquad \forall i \in I, t \in T \tag{4}$$

$$PLR_{(i,t)} = \frac{Q^{evap}_{(i,t)}}{q^{max}_{c(i)}} \qquad \forall i \in I, t \in T \tag{5}$$

Eq(1) to (5) are developed according to energy model of established commercial chillers by (Thangavelu et al., 2017).

$$W^{cwpump}_{(i,t)} = \frac{\delta_i q^{chw}_{i} h^{cwpump}}{\eta^{cwpump}_{i}} \qquad \forall i \in I, t \in T \tag{6}$$

$$W^{cdpump}_{(i,t)} = \frac{\delta_i q^{cow}_{i} h^{cdpump}}{\eta^{cdpump}_{i}} \qquad \forall i \in I, t \in T \tag{7}$$

Eq(6) and (7) are the calculation for power of chilled water pump ($W^{cwpump}_{(i,t)}$) and condenser water pump ($W^{cwpump}_{(i,t)}$) . Volume flowrate, pump head and efficiency are taken from energy audit report.

3.2 Equations for cooling tower

Cooling tower is an important unit in chiller operation to continuously reject heat from cooling water cycle in the condenser by using ambient air through forced convection. The relation between the cooling water and air cycle in the cooling tower may affect the efficiency of the chiller. Eq(8) and Eq(9) is adopted from the model by (Liu et al., 2017). The performance of cooling tower ($Q^{ct}_{(j,t)}$) is measured based on cooling tower effectiveness (ε^{air}_{j}).

$$\sum_{i \in I} Q^{cond}_{(i,t)} = \dot{m}^{air}_{(j,t)} \left(h^{air,out}_{j} - h^{air,in}_{j}\right) \qquad \forall j \in J, t \in T \tag{8}$$

$$Q^{ct}_{(j,t)} = \varepsilon^{air}_{j} \dot{m}^{air}_{(j,t)} \left(h^{sat,in}_{j} - h^{air,in}_{j}\right) \qquad \forall j \in J, t \in T$$

$$\varepsilon^{air}_{j} = \frac{\left(h^{air,out}_{j} - h^{air,in}_{j}\right)}{\left(h^{sat,in}_{j} - h^{air,in}_{j}\right)} \qquad \forall j \in J \tag{9}$$

3.3 Equations for air handling unit

The purpose of AHU is to exchange heat between chilled water from the evaporator and the mixed air in the building space. The total heat rejected by the building ($Q^{building}_{(k,t)}$) composed of two types of heat that is known as sensible heat ($SH_{(k,t)}$) and latent heat ($LH_{(k,t)}$) as shown in Eq(10) and Eq(11). $SH_{(k,t)}$ is the heat transfer equation between mixed air temperature and supply air temperature. $LH_{(k,t)}$ is the amount of energy released during phase transition according to mixed air and supply air moisture contents.

$$Q^{building}_{(k,t)} = \sum \left(SH_{(k,t)} + LH_{(k,t)}\right) \qquad \forall k \in K, t \in T \tag{10}$$

$$SH_{(k,t)} = \dot{m}^{supply}_{(k,t)} c^{SH}_{k} \left(T^{mix}_{(k,t)} - T^{supply}_{(k,t)}\right) \qquad \forall k \in K, t \in T$$

$$LH_{(k,t)} = \dot{m}^{supply}_{(k,t)} c^{LH}_{k} \left(M^{mix}_{(k,t)} - M^{supply}_{(k,t)}\right) \qquad \forall k \in K, t \in T \tag{11}$$

Eq(12) describes the mixed air temperature ($T^{mix}_{(k,t)}$) with the rise or fall degree of the surrounding air temperature ($tmix^{outside}_{t}$) during normal weather conditions. The purpose of this equation is to formulate the mixed air temperature inside the building space with the changes in surrounding air temperature.

$$T^{mix}_{(k,t)} = tmix_{k} + tmix^{outside}_{t} \qquad \forall k \in K, t \in T: t = 1$$

$$T^{mix}_{(k,t)} = T^{mix}_{(k,t-1)} + tmix^{outside}_{t} \qquad \forall k \in K, t \in T: t > 1 \tag{12}$$

The linking relation between the cooling capacity of the evaporator (i.e., cooling supply) and heat rejected by the building (i.e., cooling demand) is shown in Eq(13). Penalty variables (P_t) with high penalty costs are imposed in this equation to avoid unsatisfied cooling capacity generated from the chiller plant.

$$\sum_{i \in I} Q_{(i,t)}^{evap} = \sum_{k \in K} Q_{(k,t)}^{building} + P_t \qquad \forall t \in T \tag{13}$$

3.4 Objective function

The objective function for the optimization modelling is minimising the total electricity cost which composes of the power consumption for chiller, chilled water pump and condenser water pump. The fixed electricity tariff for commercial buildings according to tariff of TNB Berhad is used as cost coefficient (ϕ_t^{elec}) in Eq(14).

$$min \left[\sum_{i \in I, t \in T} \phi_t^{elec} \left(W_{(i,t)}^{chiller} + W_{(i,t)}^{cwpump} + W_{(i,t)}^{cdpump} \right) + \phi_t^{penalty} P_t \right] \tag{14}$$

4. Optimal operation of chiller plant – A case study of an academic building

In this part, the description of a case study is presented. The HVAC system consists of two chillers (i1 and i2) and two cooling towers (j1 and j2) that are operating simultaneously throughout the duration of air-conditioning time of 10 h from 8:00 AM until 5:00 PM (t0 - t10). The building is a 4-storey building with a total number of 17 air handling units (k1 to k17).

4.1 Description of a case study

The schematic diagram of the chillers network in HVAC system is shown in Figure 1. The chillers network involves two water cycles. The first water cycle is the condenser water. The condenser water from the cooling tower enters the condenser in the chiller to absorb heat from the chilled water. The condenser water leaves the chiller at a higher temperature and is then pushed by the pump to the cooling tower where the air is forced by the fan inside to reject heat to the environment. The condenser water then re-enters the chiller at a cooler temperature, completing the cycle. The second water cycle is the chilled water. The chilled water from the evaporator in the chiller enters the pump to distribute the chilled water around the building where it enters the air handling units (AHU). The chilled water exchanges the heat with the hot air that is collected by AHU within the building. The cold air is then released by the AHU throughout the building. Finally, this chilled water returns to the chiller at a higher temperature to complete the cycle.

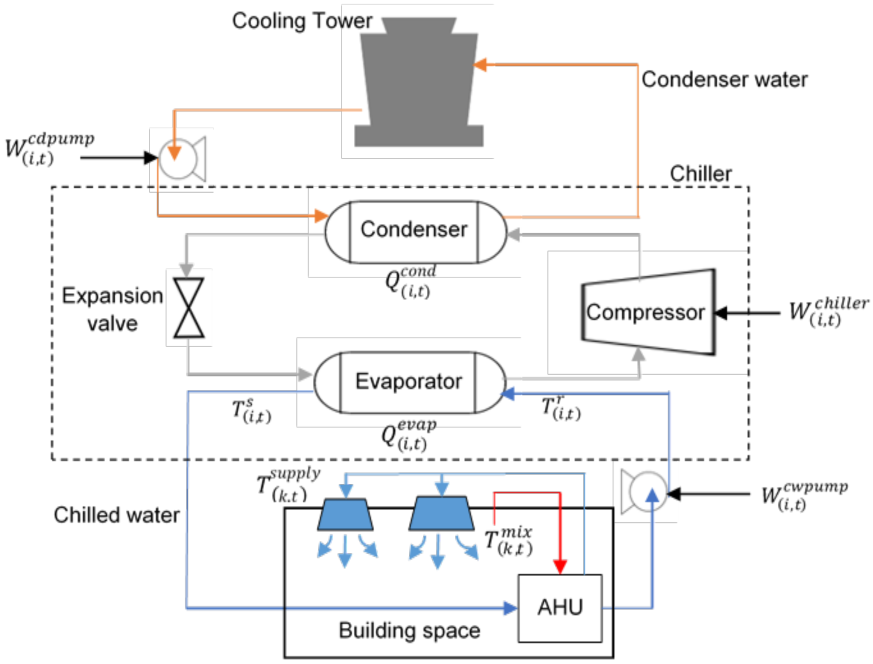

Figure 1: Schematic diagram of chillers network in HVAC system

Table 1 displays the list of input parameters for the case study. The input parameters are obtained from a recent energy audit report for an academic building in a public university in Malaysia.

Table 1: Input parameters for the case study

Symbol	Value	Description	Symbol	Value	Description
$\dot{m}_i^{chw}$	29 kg/s	Chilled water mass flow rate for chiller i1	$\dot{m}_{(k,t)}^{supply}$	7–32 kg/s	supply air flow rate from AHU to room
$\dot{m}_i^{chw}$	30 kg/s	Chilled water mass flow rate for chiller i2	$\dot{m}_i^{cow}$	23 kg/s	Condenser water mass flow rate for chiller i1
$q_{c(i)}^{max}$	536 kJ	Maximum cooling capacity for chiller i1	$\dot{m}_i^{cow}$	60 kg/s	Condenser water mass flow rate for chiller i1
$q_{c(i)}^{max}$	580 kJ	Maximum cooling capacity for chiller i2	η_i^{cwpump}	0.57	Chilled water pump efficiency
c_k^{SH}	1.21	Sensible heat coefficient	η_i^{cdpump}	0.77	Condenser pump efficiency
c_k^{LH}	3.00	Latent heat coefficient	ϕ_t^{elec}	USD 0.083 /kWh	Electricity price

4.2 Results of the case study

This case study has been solved by using the Eq(1) until (14) considering input parameters in Table 1. The optimisation problem has been solved under standard configuration and a zero optimality gap in GAMS version 38.2 by using CPLEX solver in Intel(R) Core (TM) i7. The optimal results that are obtained are analyzed and discussed below. Figure 2a shows the normalised total heat requirement of the building spaces per time. The normalized total cooling requirement is calculated by finding the ratio of cooling requirement to the maximum cooling requirement for each time. The maximum cooling requirement is at time t6 because the total sensible heat is the highest at this time due to large air temperature difference between supply air and mixed air temperature. The temperature difference in t6 was in the range of 1.11 to 1.3 times higher than that of the other time point. Figure 2b displays normalized percentage of cooling load and power input for each chiller. The maximum cooling requirement represents maximum cooling load as shown at time t6. Although cooling load at this time is maximum, the power input especially for chiller i2 is at minimum level in comparison to other time. The reason for this is because the coefficient (beta and gamma) for power input is lower at this time point.

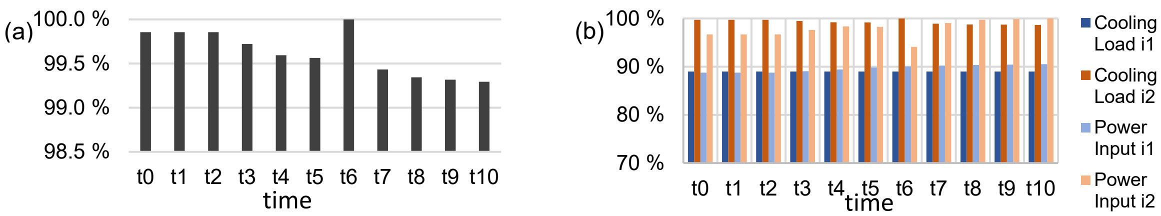

Figure 2: (a) Cooling requirement of building spaces; (b) Comparison between power input and cooling load

Table 2 shows the optimal operating condition for chiller plant specifically for time t6. The coefficient of performance (COP) for chiller i2 is better than chiller i1 because the ratio between the cooling load and power input for chiller *i2* is higher than the ratio for chiller i1. According to ASHRAE – Chiller Plant Efficiency chart (Hartman, 2001) on chiller plant performance indicator, the average COP for chiller plant is 4.87 which indicates a high-efficiency optimised chiller plant.

Table 2: Optimal operating condition for chiller plant

Chiller	Chilled water supply temperature (°C)	Chilled water return temperature (°C)	Power Input (kW)	Cooling Load (kW)	COP	Condition of chiller plant
i1	7.80	11.4	93.54	438.95	4.69	Optimal
i1	7.30	11.80	112.64	465.20	4.13	Current
i2	7.78	11.7	97.73	493.25	5.04	Optimal
i2	7.70	12.10	113.50	516.43	4.55	Current

Figure 3 shows the total electricity cost and electricity cost components comparison of the current chiller plant and the optimal result. The percentage of cost saving is around 23 %. This shows that the current electricity cost that is based on energy audit can be potentially minimised if the operating condition follows the optimized result. The percentage cost reduction is closer to 30 % for not functioning effectively. Therefore, the current chiller plant is not considered as highly efficient due to the big gap between the current and optimal chiller plant.

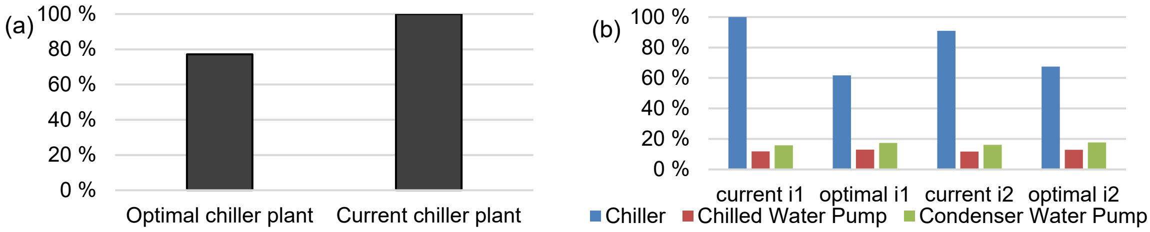

Figure 3: Comparison of (a) total electricity cost for optimal result and energy audit report (percentage); (b) electricity cost components for current and optimal chiller plant

5. Conclusions

In this study, the optimal operation of the chiller plant in an academic building has been presented by accounting for the operation of chillers, cooling towers and air handling units. From the results, it is observed that the percentage of optimal cost is lower than the current cost by about 23 %. This demonstrates a direct result of percent energy improvement that can be made by the building owner to achieve low electricity cost and enhanced energy efficiency through optimal energy consumption of the chiller plant. Therefore, this could result in obtaining high energy star rating to achieve sustainable energy practice for an academic building.

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References

Deng K., Sun Y., Li S., Lu Y., Brouwer J., Mehta P.G., Chakraborty A., 2015, Model predictive control of central chiller plant with thermal energy storage via dynamic programming and mixed-integer linear programming, IEEE Transactions on Automation Science and Engineering, 12(2), 565–579.

Energy Commission, 2017, Performance and Statistical Information on Electricity Supply Industry in Malaysia 2017, Energy Commission Malaysia, Putrajaya, Malaysia.

Hartman T.B., 2001, All-variable speed centrifugal chiller plants, Ashrae Journal, 43, 43–53.

Huang P., Huang G., Augenbroe, G., Li S., 2018, Optimal configuration of multiple-chiller plants under cooling load uncertainty for different climate effects and building types, Energy and Buildings, 158, 684–697.

Liu Z., Tan H., Luo D., Yu G., Li J., Li Z., 2017, Optimal chiller sequencing control in an office building considering the variation of chiller maximum cooling capacity, Energy and Buildings, 140, 430–442.

Sala-Cardoso E., Delgado-Prieto M., Kampouropoulos K., Romeral L., 2019, Predictive chiller operation: A data-driven loading and scheduling approach, Energy and Buildings, 208.

Shao Z., Gholamalizadeh E., Boghosian A., Askarian B., Liu Z., 2019, The chiller's electricity consumption simulation by considering the demand response program in power system, Applied Thermal Engineering, 149, 1114–1124.

Thangavelu S.R., Myat A., Khambadkone, A., 2017, Energy optimization methodology of multi-chiller plant in commercial buildings, Energy, 123, 64–76.

Theng L.M., Tan J., Liew P.Y., Tan L.S., 2021, A review of manufacturing sustainability assessment tool selection criteria: A quantitative score-rating system versus process-data sustainability assessment, Chemical Engineering Transactions, 89, 523-528.

Varbanov P.S., Klemeš J.J., Chin H.H., 2021, Minimisation of the resource demands and environmental footprints – the need for smart symbiosis networks, Chemical Engineering Transactions, 89, 421-426.

Wang W., Zhou Q., Pan C., Cao F., 2022, Energy-efficient operation of a complete chiller-air handing unit system via model predictive control, Applied Thermal Engineering, 201, 117809.