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Optimal Planning of Multi-Compressors Refrigeration System for Maximising Efficiency with the Influence of Weather Condition

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The formulation of optimisation modelling for the multi-compressors refrigeration system is studied to maximise the efficiency of the system. The main challenge to formulate actual representation of the system occurs when some assumptions are oversimplified in the model formulations. The cooling load with the effect of ambient temperatures are usually not predicted in the model formulations and it is assumed to be a constant value. The options to decide which compressor to operate or in a standby mode is usually unavailable. The reason for simplified model assumptions is due to the lack in understanding the optimization problems and limited data availability. The main aim of this proposal is to formulate a mathematical model for the whole process of the vapour compression refrigeration system and to find the maximum coefficient of performance profile. The formulation of the optimization modelling for the system is modelled as Linear Programming Model to establish an accurate representation of the theoretical process integration of each component in the system. The real-time data for energy consumption, cooling load, and the temperature deviation can be obtained from the building management system. Statistical analysis such as time-series and regression methods are applied to find the relation of energy consumption profile with the ambient temperatures. The optimization modelling is modelled in General Algebraic Modelling Software and solved by a CPLEX solver to evaluate the optimum solution. The outcome is the operational planning of the multi-compressors network over the planning time points and the optimal time-varying coefficient of performance profile for the system that is obtained from the optimal solution with the main aim of obtaining highly efficient performance of the system. The total power consumption of multi-compressors refrigeration system by 43 % in comparison to conventional operation. This study will be beneficial to systematically evaluate the potential control strategy for achieving optimal operation of the refrigeration system.

1. Introduction

The primary goal for efficient operation of refrigeration system is reducing energy consumption and saving the electricity bills. The majority of the cooling system integrates the technology of vapor compression refrigeration (VCR) and the air handling units (AHUs) of the ventilation system. The efficiency of VCR system can be evaluated by calculating the coefficient of performance (COP) as an indication to measure the energy performance of the system. In the chiller network of the VCR system, COP is the proportion between the evaporator's cooling load and the compressor's power consumption. If the ratio between the evaporator's cooling load and the compressor's power consumption is decreased, the overall COP will decrease over the operational time of the VCR system. The major factors that affect the COP values are the indoor set point temperature, outdoor temperature, and performance of each component in the system. For the multi-compressors in the

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chiller network of the refrigeration system, the major issues arise on determining the optimal chiller loading (OCL) and chiller sequencing problems.

The process integration of each component of VCR system and AHU units can be modelled as theoretical optimisation framework to find the optimal chiller sequencing and loading and the interaction of each component of the VCR system with the main aim of minimising energy consumption (Aziz et al., 2022).

Major research efforts have been done for developing modelling formulations to improve operational efficiency and minimising energy consumption of VCR system. Qiu et al. (2020) optimised the chiller loading that is based on reinforcement learning method. In similar study, Acerby et al. (2020) developed algorithm for optimal chiller loading with the assumption of quadratic curve for power consumption of the chiller. COP prediction model and chiller sequencing framework was proposed by Zheng et al. (2022). In a recent study, Wang et al. (2022) formulated model predictive control to provide optimal inputs to the system by coordinating the operation of chiller to well-maintained the room temperature. The simulation results for all literary works showed significant energy reduction and electricity saving. Some limitations still exist mainly on the assumptions of the model formulations that are not properly predicted or oversimplified especially the relation of space temperature from AHUs and weather conditions over the operational times of the chiller system. In this paper, modelling formulation for optimal chiller loading and sequencing for multi-compressors refrigeration system is developed that considers weather conditions and space temperatures to obtain optimal planning for chillers operation and time-varying COP profiles. The optimisation model in this study is the extended version of the previous study (Zulkafli et al., 2023). The improvement made from the previous optimisation model is the operational status model for the chillers that can be categorised into three operational modes. The research gap of this study is fulfilled by considering the space temperature and weather condition with operational times of the chillers in the VCR system.

2. Optimisation problem and model formulations

The main aim of the optimisation modelling for vapour refrigeration system with chillers network is to find the best operational planning with minimum electricity costs and to obtain optimal time-varying COP profiles based on different weather condition. The optimisation model is defined by the following items: (i) the time point starts at t1 (8:00 AM) until t55 (5:00 PM) with every time point is 10 min time interval; (ii) two chillers with operational status of either in starts mode, in operation, or in shutdown mode; (iii) minimum and maximum chilled water supply and return temperatures for each chiller; (iv) two cooling towers with given effectiveness; (v) seventeen air handling units (AHUs) with minimum and maximum return and supply air temperatures; and (vi) a fixed rate for electricity tariff. For every time point, the optimal decisions are the operational status of the chillers, total cooling demand, evaporators' cooling load, compressors' power consumption, sensible and latent heat of the building spaces from AHUs, the chillers' partial load ratios and the electricity costs of the whole operation of vapour compression refrigeration (VCR) system.

The optimisation model is built as a mixed integer linear programming (MILP) model to represent operational status and conditions of the chillers. In comparison to the previous study, the building management system (BMS) provides a new set of parameters for this study. The resulting optimization model is modelled using General algebraic modelling system (GAMS) version 38.2.1 is used to model the optimisation model. The Intel(R) core (TM) i7 computer is used to solve the model. The optimisation model must be proven to be feasible to obtain the best solution under standard configurations and a zero optimality gap. The whole system is to be considered for accurate representation of the VCR system. In this paper, new formulated model that is incorporated in the original model formulation is discussed.

2.1 Equation for operational modes of chillers network

The categories for the operational modes of the chillers network are the starts mode ($X_{(i,t)}^{start}$), in operation mode ($X_{(i,t)}^{op}$), and shutdown mode ($X_{(i,t)}^{shut}$). Eq(1) and Eq(2) describe the logical connection in the forms of binary variables of starts, in operation and shutdown modes of each chiller for each time point.

$$X_{(i,t)}^{start} - X_{(i,t)}^{shut} = X_{(i,t)}^{op} - \varphi_{(i,t)}^{op} \qquad \forall i \in I, t = 1 \tag{1}$$

$$X_{(i,t)}^{start} - X_{(i,t)}^{shut} = X_{(i,t)}^{op} - X_{(i,t-1)}^{op} \qquad \forall i \in I, t > 1 \tag{2}$$

$$X_{(i,t)}^{start} + X_{(i,t)}^{shut} \leq 1 \qquad \forall i \in I, t > 1 \tag{3}$$

The binary variables value is either 1 that means the variable is activated or 0 which means otherwise. For example, if the chiller is in starts mode, ($X_{(i,t)}^{start} = 1$) chiller is in operation as well ($X_{(i,t)}^{op} = 1$).This will mark $X_{(i,t)}^{shut} = 0$. Chiller can either be in a starts mode or in a shutdown mode for a time period. According to Equation (3), only $X_{(i,t)}^{start}$ or $X_{(i,t)}^{shut}$ can be equal to 1. The parameter value of $\varphi_{(i,t)}^{op}$ will always be zero (off mode) when starting up for this case study. The necessity to maintain this parameter in the optimisation model is to represent a general optimization model that can be implemented in other case study especially for manufacturing industries with continuous chiller operations.

2.2 Equation for chillers network

Eq(4) shows the chillers network's equation for cooling load. The operation mode ($X_{(i,t)}^{op}$) is included in both Eq(5) and Eq(6) that represents the lower and upper limits for the chilled water supply ($T_{(i,t)}^{s}$) and return ($T_{(i,t)}^{r}$) temperatures. The values for chilled water supply and return temperatures will only be considered in the optimisation solutions when the chiller is operating for a specified time point.

$$Q_{(i,t)}^{evap} = \dot{m}_{(i,t)}^{chw} c_i^w \left(T_{(i,t)}^r - T_{(i,t)}^s\right) \qquad \forall i \in I, t \in T \tag{4}$$

$$\alpha_{(i)}^{r,min} X_{(i,t)}^{op} \leq T_{(i,t)}^r \leq \alpha_{(i)}^{r,max} X_{(i,t)}^{op} \qquad \forall i \in I, t \in T \tag{5}$$

$$\alpha_{(i)}^{s,min} X_{(i,t)}^{op} \leq T_{(i,t)}^s \leq \alpha_{(i)}^{s,max} X_{(i,t)}^{op} \qquad \forall i \in I, t \in T \tag{6}$$

The power consumption of the chiller is seen in Eq(7). The gradient coefficient ($\beta_{(i,t)}$) and the intercept coefficient ($\gamma_{(i,t)}$) of power consumption are extracted using the regression analysis.

$$W_{(i,t)}^{chiller} = \beta_{(i,t)} \left(T_{(i,t)}^r - T_{(i,t)}^s\right) + \gamma_{(i,t)} X_{(i,t)}^{op} \quad \forall i \in I, t \in T \tag{7}$$

The coefficient values are obtained by plotting historical cooling load data against the chilled water temperature deviation. Eq(7) is considered to account for the electricity used by the chiller when it operates.

$$W_{(i,t)}^{cwpump} = \left(\frac{\delta_i q_i^{chw} h^{cwpump}}{\eta_i^{cwpump}}\right) X_{(i,t)}^{op} \qquad \forall i \in I, t \in T \tag{8}$$

$$W_{(i,t)}^{cdpump} = \left(\frac{\delta_i q_i^{cow} h^{cdpump}}{\eta_i^{cdpump}}\right) X_{(i,t)}^{op} \qquad \forall i \in I, t \in T \tag{9}$$

The pump head, volume flow rate and pump efficiency are all assessed form historical data of energy audit report. Eq(8) states the total power consumption for chilled water pump ($W_{(i,t)}^{cwpump}$) and Eq(9) express the total power consumption for condenser water pump ($W_{(i,t)}^{cdpump}$). Other equations such as the equations for cooling tower, air handling units and objective function are the same as in the previous study. The main aim of this study is to propose the optimal operational planning for multi-compressors refrigeration system that are based on the cooling demand by the building for different weather condition with the major aims of reducing energy consumption and electricity bills.

3. Operational planning for VCR system

The chillers network of VCR system includes two chillers (i1 and i2) . The main components in every chiller is the compressor, evaporator and the condenser. The VCR system is integrated with two cooling towers (j1 and j2) and 17 AHUs (k1 until k17). The operational time is 8 h with 10 min time interval (t1 until t55). The time point starts at 8:00 AM and end at 5:00 PM.

3.1 Description of a case study

Figure 1 displays the chillers network system for vapor compression refrigeration system. The VCR cycle starts with the compression process of the superheated refrigerant vapor in the compressor to increase its temperature and pressure. The refrigerant vapor enters condenser to remove heat by condensation process at constant temperature and pressure. The refrigerant changes its phase from superheated vapor to sub-cooled liquid. The expansion valve reduces the pressure and temperature of the liquid refrigerant that has been subcooled. The cold saturated mixture of the refrigerant travels through the evaporator where it is vaporized by the warm air of the building spaces. The refrigerant changes its phase from saturated mixture to vapor and returns to compressor to complete the VCR cycle.

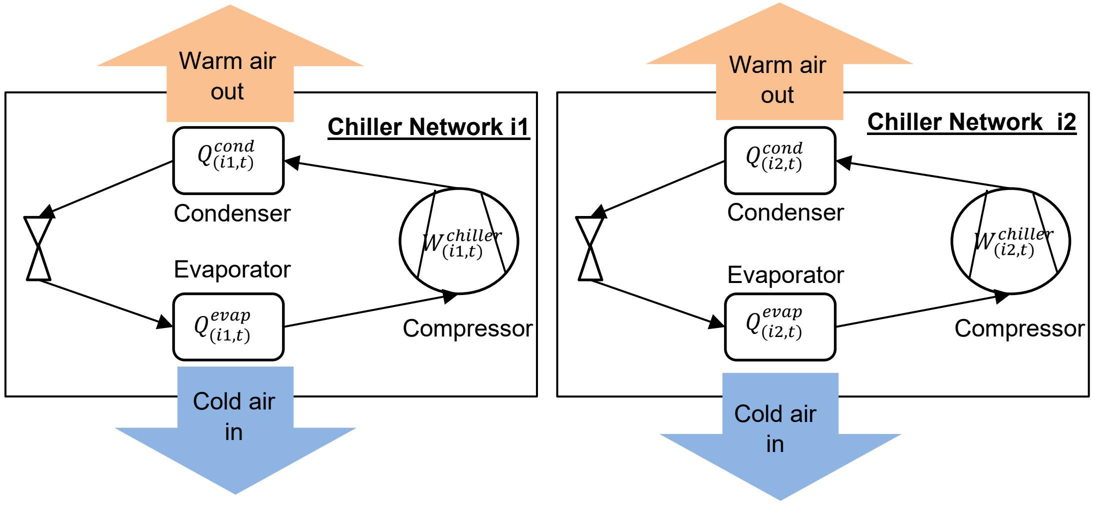

Figure 1: Chillers network in parallel for vapour compression refrigeration system

Table 1 shows the main parameters of the case study. The data for the main parameters for the operational planning of refrigeration system is taken from energy audit, building management system (BMS) and correlations calculation.

Table 1: Main parameters for the case study

Symbol	Descriptions	Values	Sources
$\varphi^{op}_{(i,t)}$	Operational status at the beginning of planning time points	0	Energy audit
c^{w}_{i}	Water specific heat	4.18 kJ/kg.K	Energy audit
$\alpha^{r,min}_{(i)}$	Minimum chilled water return temperature	12	BMS
$\alpha^{r,max}_{(i)}$	Maximum chilled water return temperature	14	BMS
$\alpha^{s,min}_{(i)}$	Minimum chilled water supply temperature	7	BMS
$\alpha^{s,max}_{(i)}$	Maximum chilled water supply temperature	8	BMS
$\dot{m}^{chw}_{(i,t)}$	Mass flow rate for chilled water	24 – 32 kg/s	BMS

4. The optimal solutions for the operational planning of VCR system

Figure 2 displays the optimal operational planning of VCR system that is segregated into three weather conditions which is in the morning from 8:00 until 11:50 h afternoon from 12:00 to 13:50 h, and late afternoon that begin at 14:00 until 17:00 h.

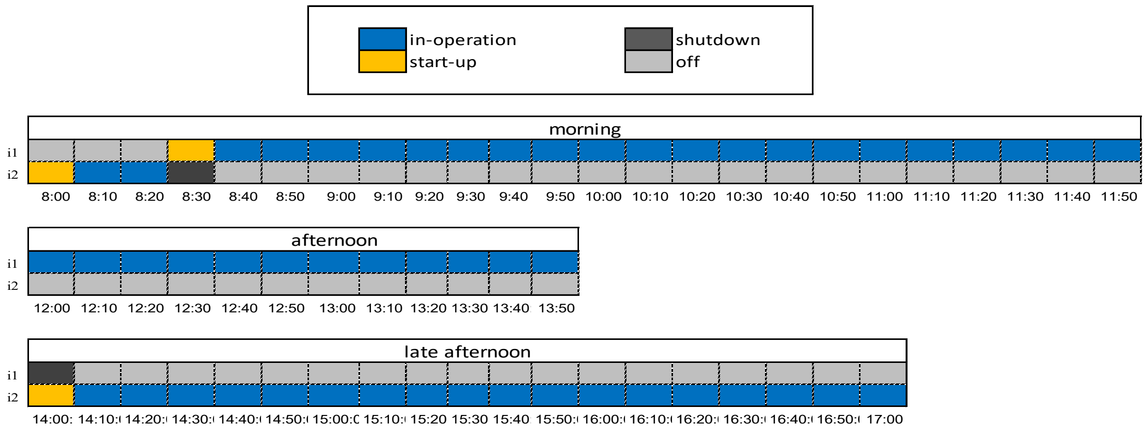

Figure 2: Optimal operational planning of VCR system in commercial building

The status of operation of either starts-up, in operation or shutdown is indicated by the different color blocks. During the operation of the refrigeration system for each of weather condition, only one chiller is in operation since it can completely meet the cooling requirement determined by measuring the building's sensible and latent heat. The total energy consumption will be greatly reduced because only one chiller is running instead of two chillers during conventional normal practice. The frequent switching between the chillers that happen in the operational planning of the VCR system is based on the performance of the chiller at that point of time. The chiller is selected to operate at point of time if minimum amount of power consumption is required while at the same time satisfying cooling demand of the building spaces.

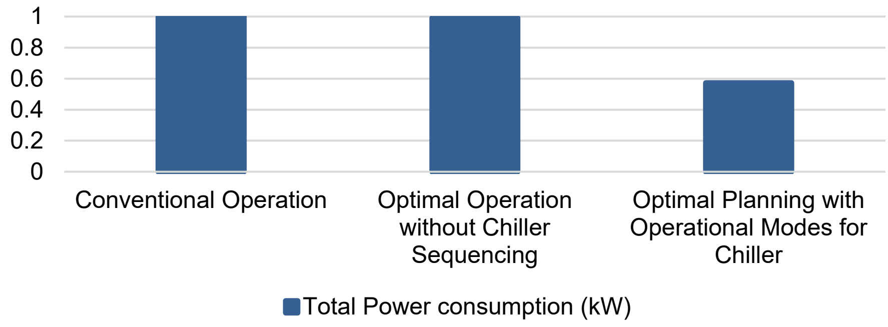

Figure 3: Total power consumption for alternative operations of multi-compressors refrigeration system

Figure 3 displays total power consumption for three alternative operations condition for the multi-compressors vapor compression refrigeration system. The conventional operation is the currently normal practice of the VCR system in which both compressors are operating at the same time. The result for the optimal operation without chiller sequencing is obtained from previous research work (Zulkafli et al., 2023). The optimal planning with operational modes for compressors in chillers network of VCR system is the improvement made for this study. From the comparison of total power consumption for alternative operations, the optimal solution with operational modes for chillers network shows substantial reduction of 40 % and 43 % in comparison to optimal operation without chiller sequencing and conventional operation.

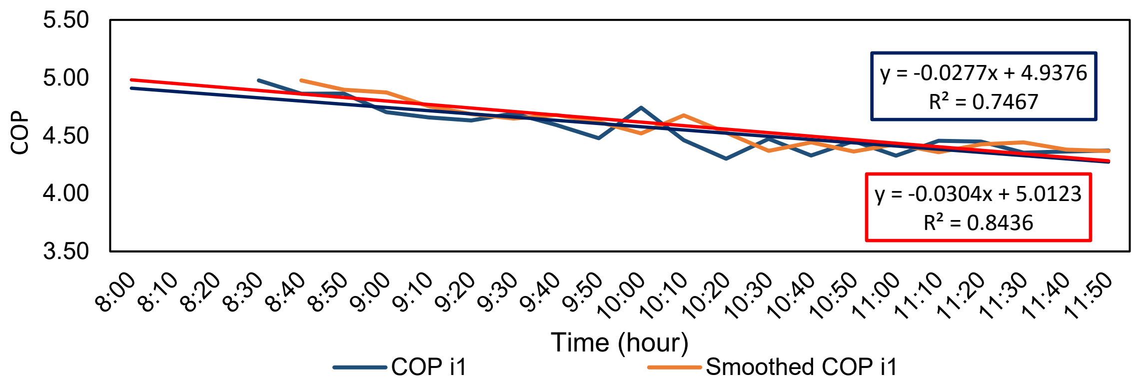

Figure 4: Optimal time-varying COP profiles for compressor i1 of chillers network

The optimal time-varying COP profile for compressor i1 is shown in Figure 4 by using time-series analysis. The COP profiles are taken from the optimal results of this work. The smoothed COP profiles are plotted in the same graph with smoothing factor of 0.7. The purpose of time series analysis for the COP profiles are to smooth out the optimal COP profiles to identify its trends in a linear form of a time series. For compressor i1 in the chillers network of VCR system, the smoothed COP profile predicts decreasing trend during the morning timeframe with high coefficient of determination of 0.84. The decreasing COP trend in the morning timeframe is due to higher ratio of the evaporator's cooling load to compressor's power consumption. The cooling load at the beginning of chiller operation in early morning is higher than the cooling load at the later morning timeframe because high cooling load is needed for cooling the spaces to meet the specification of air set point temperature during the startup operation of the chiller network in early morning.

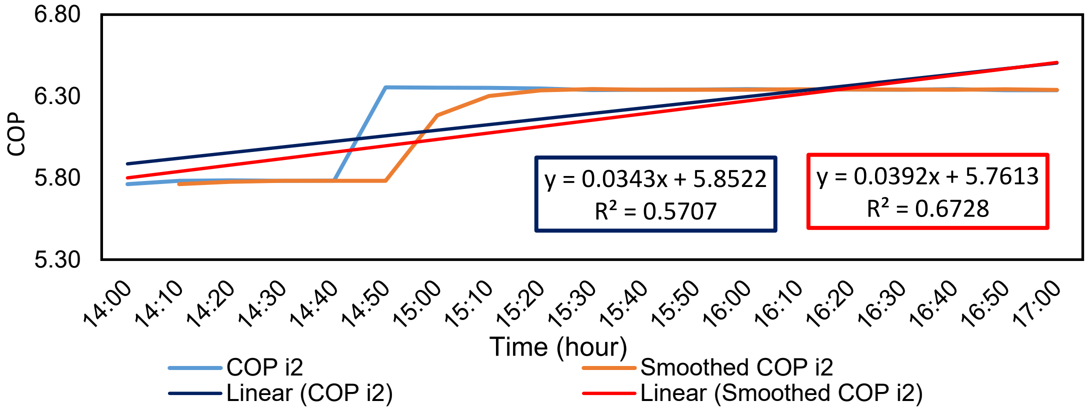

Figure 5: Optimal time-varying COP profiles for each chillers network using time series analysis

Figure 5 displays the COP profiles for each chillers network of VCR system by using time series analysis. The smoothed COP profile for compressor i2 in the chillers network shows increasing trend during the afternoon timeframe with medium coefficient of determination of 0.67. The increasing COP trend because of the lower evaporator's cooling load to the compressors' power consumption ratio. The average values for COP profiles for compressor i1 and i2 are 4.5 and 6.1.

5. Conclusions

The optimal planning for multi-compressors refrigeration system is developed with the operational modes of the chillers network. The results demonstrate the cooling demand of the building spaces can be satisfied by the operation of only one compressor in the chillers network of VCR system in each time point. This reduces total power consumption of multi-compressors VCR system by 43 % in comparison to conventional operation while maintaining the space temperature. All equipment in VCR system is assumed to be in a clean condition and the external factors that may influence the performance of the chiller is excluded in this study. The proposed optimal planning for multi-compressors in chillers network of VCR system is expected to implement as a practice demonstration for the HVAC system in a commercial building. The potential risk for this case study is the power outage, if any. The generator will be on a stand-by mode to provide continuous supply of electricity during the power outage. The future study will focus on the implementation of optimal variables in real chillers plant and to include time-varying electricity tariff such as Time-of-Use tariff with peak and off-peak values.

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References

Acerbi F., Mirco R., Giuseppe D.N., 2020, An Exact Algorithm for the Optimal Chiller Loading Problem and Its Application to the Optimal Chiller Sequencing Problem, Energies, 13(23), 6372.

Aziz D.H.C., Zulkafli N.I., Razak N.H., Klemeš J.J., 2022, Optimal Fertigation for Automated Fertilizer Blending System by Minimising Fertilizer Cost and Utility Consumption, Chemical Engineering Transactions, 94, 115-120.

Shunian Q., Li Z., Zhengwei L., Zhang X., 2020, Model-Free Optimal Chiller Loading Method Based on Q-Learning, Science and Technology for the Built Environment, 26(8), 1100–1116.

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.

Zheng Z., Chen Q., Cheng F., Guan N., Vishwanath A., Wang D., Liu F., 2022, An Edge Based Data-Driven Chiller Sequencing Framework for HVAC Electricity Consumption Reduction in Commercial Buildings, IEEE Transactions on Sustainable Computing, 7(3), 487–98.

Zulkafli N.I., Sukri M.F., Mohd Tahir M., Muhajir A., Hanak D.P., 2023, Performance Analysis and Optimisation of the Chiller-Air Handling Units System with a Wide Range of Ambient Temperature, Cleaner Engineering and Technology, 14, 100643.