Optimization of MVAC Systems for Energy Management by Evolutionary Algorithm

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Abstract: *Energy management in existing building services installations is an essential focus of the contemporary facilities management. The subway company that is one of the major utilities services in Hong Kong Special Administrative Region (HKSAR) has considered better energy management schemes in its subway stations to reduce the running cost. In the past few years, in order to achieve energy saving in the stations, some feasible measures in the Mechanical Ventilation and Air Conditioning (MVAC) systems were implemented, however the engineering decisions were supported by the trial-and-error or imprecise estimation. Improvement to this process would be possible if numerical optimization methods were to be used. Evolutionary algorithm coupled with external plant simulation programme, was applied to determine the optimum conditions of the essential parameters of the MVAC systems in a holistic energy management approach. For the centralized MVAC systems of the subway stations under studies, the developed optimization and simulation model was found useful to appraise the energy management opportunities for effective design and facilities management.*

Keywords: Evolutionary algorithm, optimization, energy management, MVAC systems.

1.0 INTRODUCTION

1.1 Promotion of Energy Management Opportunities

Effective energy management in existing building services installations becomes a primary focus of facilities management, not just because of the environmental and sustainable concerns, but also due to the adverse impact of the global economic recession in these few years. In Hong Kong Special Administrative Region (HKSAR), such influence has not only bound to the commercial and industrial sectors, but even to the utilities companies. The Electrical and Mechanical Services Department of HKSAR government has promoted a series of energy management schemes, one of them is to identify the energy management opportunities (EMOs) through energy audits. There are three categories of EMOs: Category I requires no or insignificant capital investment to implement; Category II can be carried out at relatively low cost; and Category III needs significant capital investment but reasonable payback period. Therefore there is a great priority and motivation to seek for the EMOs of Category I which may have insignificant investment implication but possible cost saving. In typical Heating, Ventilating and Air Conditioning (HVAC) systems, this category practically involves the ideas such as to readjust the operating conditions like space air temperature, supply air flow rate, chilled water supply temperature, etc. without sacrificing the built comfort requirements; to reset those operating conditions in the mid-seasons and during the non-peak periods; to reduce the operating time of the equipment not affecting the normal operation; or to minimize the night mode operation of the major equipment.

The choice of the EMOs of Category I depends on the system design, provisions and complexity. These EMOs can be implemented immediately, and their effects in energy saving can be evaluated quickly. However in readjusting the operating conditions of the main equipment, it may render to contradictory situation. For example, increase of supply air temperature due to raising chilled water supply temperature would save energy in chillers, but the supply air flow rate hence energy consumption of air side equipment would be increased accordingly. This may counter-balance the advantage of the temperature adjustment in water side. So suitable optimization models are needed in order to consider the changes of different parameters in a holistic approach, and the objective of energy saving can be really achieved.

1.2 Usefulness of Optimization and Plant Simulation Models

The subway company that is one of the major utilities services in HKSAR, has considered better energy management in its subway stations to reduce the running cost. In the past few years, in order to achieve energy saving, some feasible measures in the Mechanical Ventilation and Air Conditioning (MVAC) systems were implemented by the subway company, for instance, to increase the space air temperatures of different function areas, and to readjust the time of start/stop of the MVAC systems. Although all those measures were adopted without sacrificing thermal comfort within the spaces, the engineering decisions were supported by the trial-and-error or imprecise estimation. And it depended on whether the operators could exercise the appropriate judgement in making the parametric changes and interpreting the results correctly. Therefore it would be better to use more robust tool to determine the satisfactory operating conditions and improvement schemes.

Nowadays, computer-based simulation is becoming increasingly popular and more designers and clients use this approach to evaluate the design alternatives (Kennett 2001) and year-round energy consumption (Fong *et al* 2001). For design and operation optimization, a radical breakthrough would be possible if numerical optimization methods were used instead of operator judgement. Recent advancement in plant simulation model and development in optimization model would enable such problems to be tackled using appropriate optimum-seeking methods. Among different optimization methodologies, evolutionary algorithm (EA) has been found useful in a variety of problems (Michalewicz and Fogel 2000), and they are able to handle common HVAC scenarios that often have discontinuous, non-linear and highly constrained characteristics in the search spaces.

The plant simulation package TRNSYS was used to model the whole MVAC systems including the chiller plant, water side, heat rejection and air side systems. In addition, EA was applied to determine the optimum conditions of the essential parameters of the MVAC systems in order to provide a holistic energy management approach. The external plant simulation program TRNSYS was intentionally coupled with EA for evaluating the fitness of different parametric combinations. The results would suggest the solutions for the EMOs of these subway stations.

1.3 MVAC Systems of Subway Stations

This study was focused on the MVAC systems including a 6000 TR central chiller plant and the corresponding air side systems serving 5 subway stations in the urban line. The schematic diagrams of the central chiller plant and the air side system are shown in Figures 1 and 2 respectively, and the features are summarized as follows:

a. The 5 subway stations were served by a central chiller plant which consisted of 6 numbers of 1000 TR water-cooled chillers, each had an associated constant speed chilled water pump. Differential pressure bypass circuit was applied.

b. For heat rejection, a cooling water pump was used to serve a group of 2 chillers, and carried heat to a plate heat exchanger, in which heat was removed by a sea water pump. Therefore there were altogether 3 sets of pumps and heat exchangers. Both the cooling water and sea water pumps had constant speed.

c. For the air side system, the supply air was used to handle cooling loads from two major sources in sequence: the platform and the trains. Firstly the platform cooling loads were tackled to maintain a platform space temperature T_s, which were checked against the pre-set platform design temperature T_p. On the other hand, return air grilles were intentionally installed under the platform and above the air-cooled condensers of the subway trains, so as to tackle the cooling loads from the trains, as shown in Figure 2.

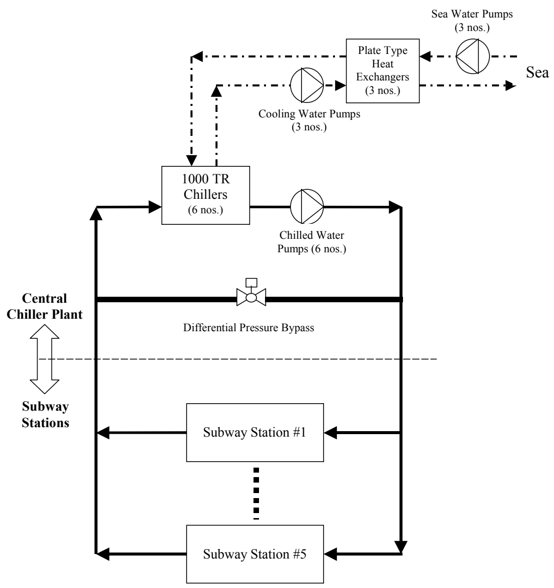

Figure 1: Central Chiller Plant and Chilled Water Distribution

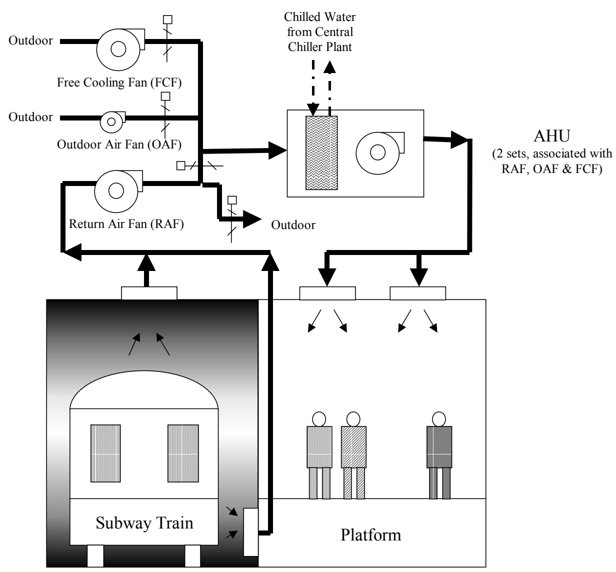

Figure 2: Air Side System of a Typical Subway Station

2.0 PLANT AND ENERGY SIMULATION

With the simulation package TRNSYS, the plant and energy simulation model of the subway stations were developed according to the actual MVAC installations and operations, and the characteristics are summarized as follows.

a. Since it was not a dynamic simulation, all the operation conditions of different equipment were determined by the hourly cooling loads and outdoor air conditions, and the simulations were generated in steady state at the corresponding hours as illustrated in Figures 3 and 4. For each operating hour, total energy consumption was the sum of energy consumptions of all the major operating equipment, and the year-round energy consumption was the sum of all 8760 hours.

b. For part load control of the chillers and pumps, the control signals were determined by the amount of hourly cooling loads as shown in Figure 3.

c. From full load to part load of the air side system, there were 4 strategies based on different loading situations:
   - Full load cooling mode: AHU working in full speed.
   - Part load cooling mode: AHU operating in half speed.
   - Full load free cooling mode: free cooling with all fans in full speed.
   - Part load free cooling mode: free cooling with all fans in half speed.

   The change from full to half speed was determined by comparing T_s against T_p (with deadband 1 °C). The change from normal to free cooling mode was based on the outdoor enthalpy h_o lower than the actual platform space air enthalpy h_s (with deadband 2 kJ/kg). These full and part load control strategies are shown in Figure 4.

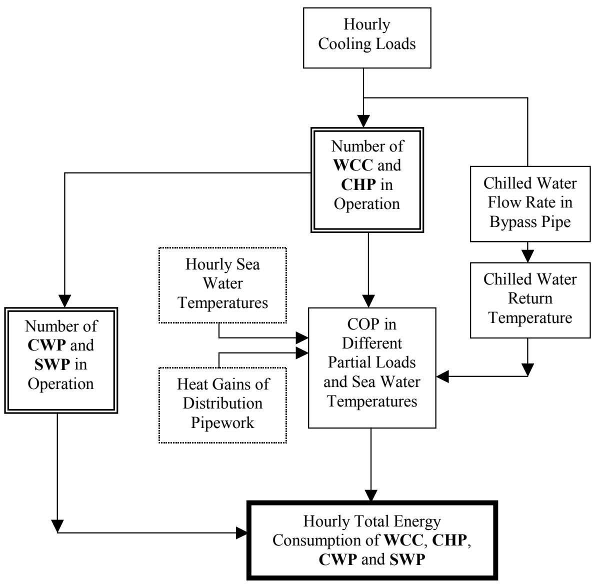

Figure 3: Determination of Energy Consumption in Central Chiller Plant

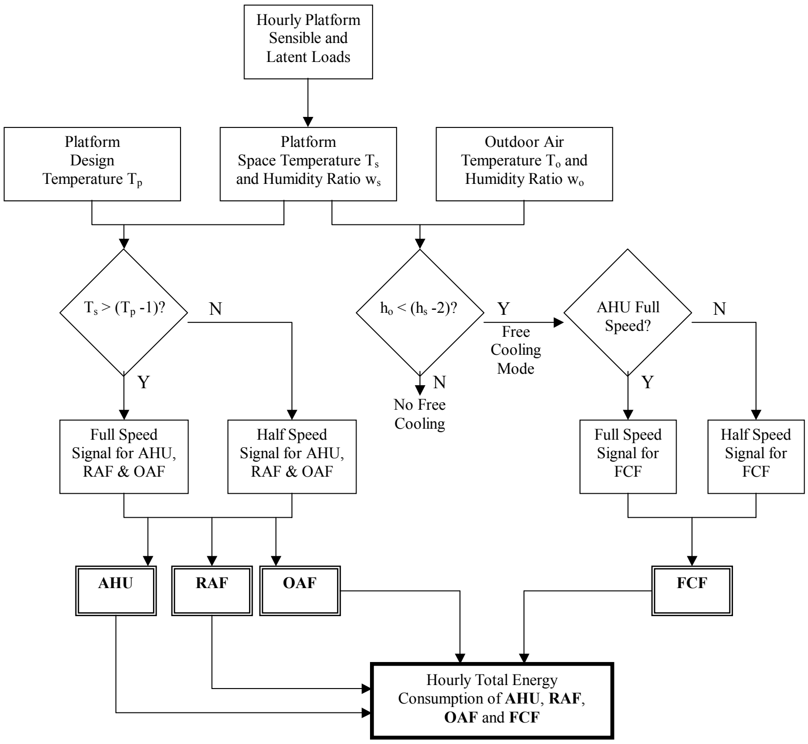

Figure 4: Determination of Energy Consumption in Air Side System

3.0 EVOLUTIONARY ALGORITHM

3.1 Development of Optimization Techniques

The best optimization model should be both efficient and effective to determine the optimum conditions within the search space, approaching to the global optimum instead of the local ones. The optimization techniques have been developed for many years, from gradient-based methods, direct search methods (Hanby and Wright 1989) to the recent random and evolutionary approaches (Wright 1996). EA becomes a popular stream of optimization techniques recently, and it includes the genetic algorithm, evolutionary programming and evolution strategy (Bäck *et al* 1997). Their differences depend on the emphasis and approach adopted for selection, recombination and mutation. Basically genetic algorithm and evolutionary programming are generally implemented in probabilistic and stochastic approach, while evolution strategy is deterministic during the selection stage. Although it seems impossible to find a single method which can be applied in all problems (Bäck *et al* 2000), application of EA is effective in handling many HVAC problems with discrete, non-linear and highly constrained characteristics (Michalewicz and Fogel 2000).

3.2 EA Coupled with Plant Simulation Model

The developed EA was real-coded, and handled floating point and integer variables by the use of variation operator. Modularity was the major characteristic, therefore the optimization model was developed by MATLAB which could effectively handle the parametric matrices across different generations. The plant simulation model was not integrated into the EA, but was coupled together and communication between these two modules was via an operating system call. There were four main constituents in this EA, they were initialisation, evaluation, selection and variation. The flow chart of the developed EA model is shown in Figure 5.

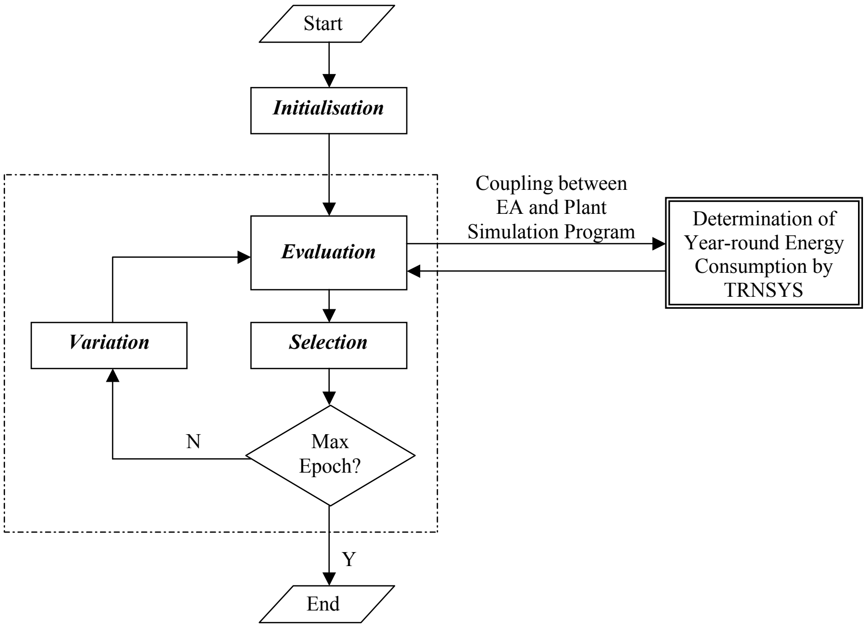

Figure 5: Flow Chart of EA Coupled with Plant Simulation Model

a. Initialisation

Before starting the search for the optimum parameters, some basic information was decided:

i. Parameters to be optimized;
ii. lower and upper bounds of each parameter;
iii. population in each epoch; and
iv. maximum number of epoch to be investigated.

In EA, each set of parameters to be optimized was treated as an individual, and the required number of individuals formed the population for each epoch of search. The stochastic nature of EA means that larger number of population would result better choice of elites without trapping at local optimal. Similarly larger number of epoch would guarantee the convergence of parameters contained in individuals. However the running time of optimization was compromised for this case, since the dominating processing time was not in EA itself, but in the plant simulation program already coupled with EA for evaluation purpose.

At the very beginning of the optimization, an initial population of individuals for investigation was produced. This initial group (first epoch) of individuals was generated randomly within the corresponding specified ranges of those parameters involved.

b. Evaluation

In general, an evaluation function should be developed and incorporated in this step in order to give the optimum and feasible solutions. In this study, since the overall year-round energy consumption of the subway MVAC systems was the ultimate target, and optimization was simply to determine the minimum energy amount. Therefore each set of feasible parameters within the population should be input into the plant simulation program so that the evaluation solution could be determined and compared in the following stage.

The main feature of this evaluation process was being coupled with the external plant simulation program TRNSYS, so operating system call was involved between EA and the plant simulation program for each individual within the population in every epoch. This was the most time-consuming step for the complex simulation problems, for instance it took about 15 minutes to run a full set of 8760-hour energy consumption for the entire MVAC systems of the subway stations for an individual being assessed. No matter how efficient was the programming of EA and how fast was the processing speed of the computer, the bottleneck was the number of hours involved in a year-round study, so the frequency of simulation could not be reduced and the running time of the entire optimization model could not be advanced significantly.

c. Selection

After evaluation, selection of the individuals for variation should be carried out. Selection is a process to determine the next population based on current individual's quality. It can be carried out in either stochastic or deterministic way. The stochastic approach would generate a probability function, e.g. through Roulette Wheel, over the possible compositions for next epoch; while the deterministic approach would develop the next generation according to the prescribed composition of parents and offspring.

As a preliminary study in this case, the selection process was carried out in the following ways:

i. The philosophy of elitism was applied and the fittest individual was placed into the next epoch without any variation.
ii. The remaining individuals were all carried forward for variation.

d. Variation

In variation, suitable variation operator should be selected for the problem, and it is crucial to generate new population of individuals which would approach the true optimum but not trapped by local ones. This step has the same purpose of crossover (mating) and mutation in genetic algorithm (Wright 1996), for acquiring offspring with better fitness from parents in probabilistic approach. In addition, after applying variation operator, appropriate constraint handling technique is used in order to effectively highlight the feasible and fittest individuals, and repair the infeasible ones back to the search range.

In this study, Gaussian-distributed random number was applied as the variation operator since it was proven to be effective in perturbations and mutation (Michalewicz and Fogel 2000). This number has a mean of zero and a dynamic standard deviation, and offspring were "born" by adding it to the parents. An initial range was set for the random variation of each parameter, and the standard deviation factor σ which decreased exponentially with each epoch was applied. This factor was determined as follows:

$$\sigma = e^{-\frac{g-1}{c}} \tag{1}$$

where, g = epoch
c = constant

On the other hand, constraint handling technique was applied for any infeasible parameter which was out of its specified range, and it was reset back to the respective lower or upper bound that was nearer to the mutated value. This generally occurred in the early stages of the search, before the standard deviation factor σ was reduced significantly.

4.0 OPTIMIZATION FOR ENERGY MANAGEMENT

Based on the developed EA optimization and simulation model of the MVAC systems for the subway stations, optimization of different operating parameters could be carried out. The results were used to check against the existing operating conditions, and optimum settings could be suggested for the EMOs of Category I. After thorough appraisal of the currently installed equipment, operating speeds of the chilled water pumps, cooling water pumps and sea water pumps were all constant, so there was little chance to change the related parameters. For the major air side equipment, 2-speed fans were used, and the algorithm of changing speed was already incorporated into the plant and energy simulation model, so there was also little opportunity to optimize their parameters. Finally there were two essential parameters which could be investigated through optimization:

- The set point of chilled water supply temperature of chiller T_{cws}; and
- the platform design air temperature T_p.

For the existing plant operation of the subway stations, the set points of T_{cws} and T_p were 7.2 °C and 27 °C respectively. Although in the optimization model the number could be accurate up to many digits, it was meaningless to determine the optimum settings in such details. Since the resolution of the installed central control system of the subway stations was just up to the first decimal place in both T_{cws} and T_p, so the degree of convergence in optimization would be based on one-tenth degree C.

4.1 Input Data

For the developed EA model, the following input data were used in optimization:

Lower bound of T_{cws}:	6 °C
Upper bound of T_{cws}:	8 °C
Lower bound of T_p:	25 °C
Upper bound of T_p:	27 °C
Population:	10
Maximum epoch:	20

For T_{cws}, the range of 6 - 8 °C was used since it was common in practice to balance the required dehumidification effect in air side and good efficiency of chillers. For T_p, since the maximum platform design temperature should not be higher than 27 °C, so it was set as the upper bound. The lower bound was preliminarily set according to the temperature difference of 2 °C as that of T_{cws}. Since the optimization running time was mainly the plant simulation time, the numbers of population and epoch were determined by compromising the stochastic selection and variation, and the efficient convergence of T_{cws} and T_p.

4.2 Optimization Results

Based on the developed EA optimization and simulation model, the optimization results of the MVAC systems of the subway stations were determined, and those of year-round energy consumption, T_{cws} and T_p are presented in Figures 6, 7 and 8 respectively.

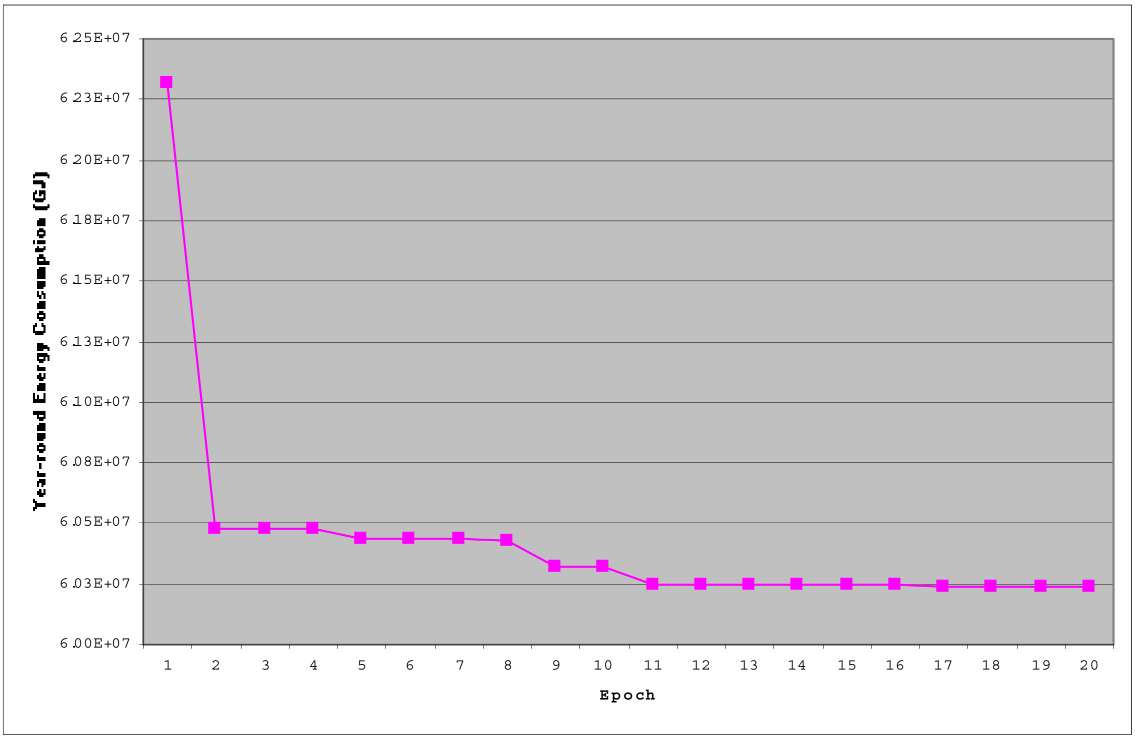

Figure 6: Optimum Year-round Energy Consumption in Each Epoch

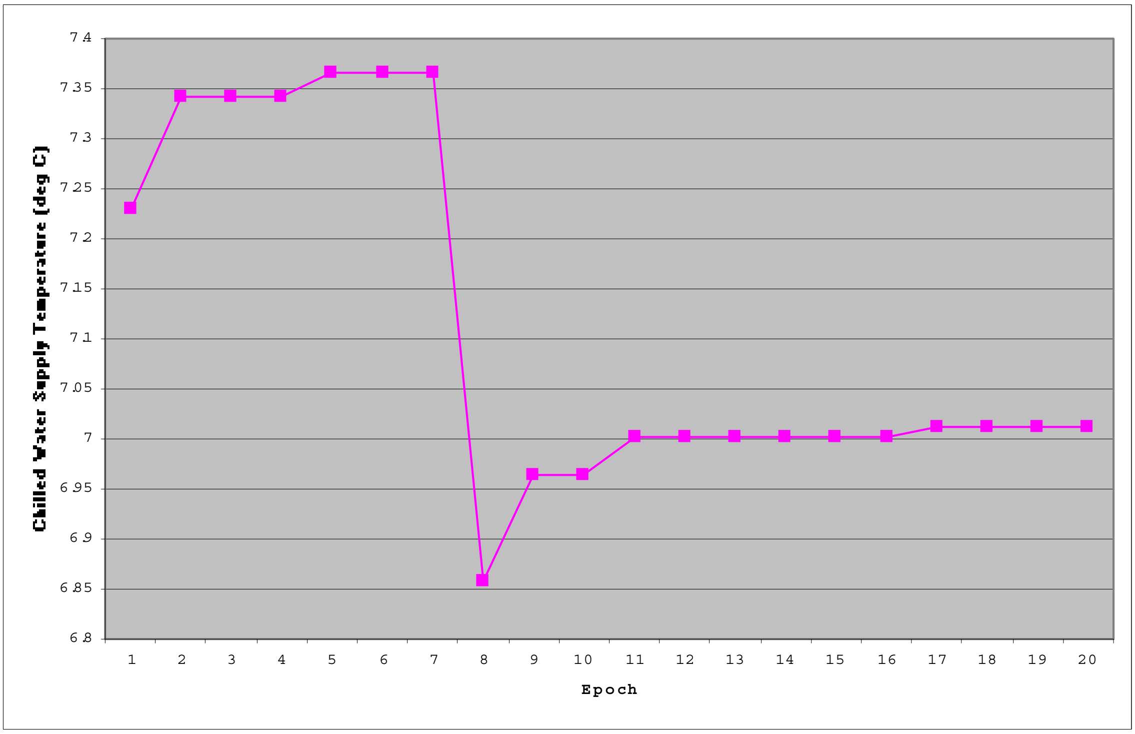

Figure 7: Optimum Chilled Water Supply Temperature in Each Epoch

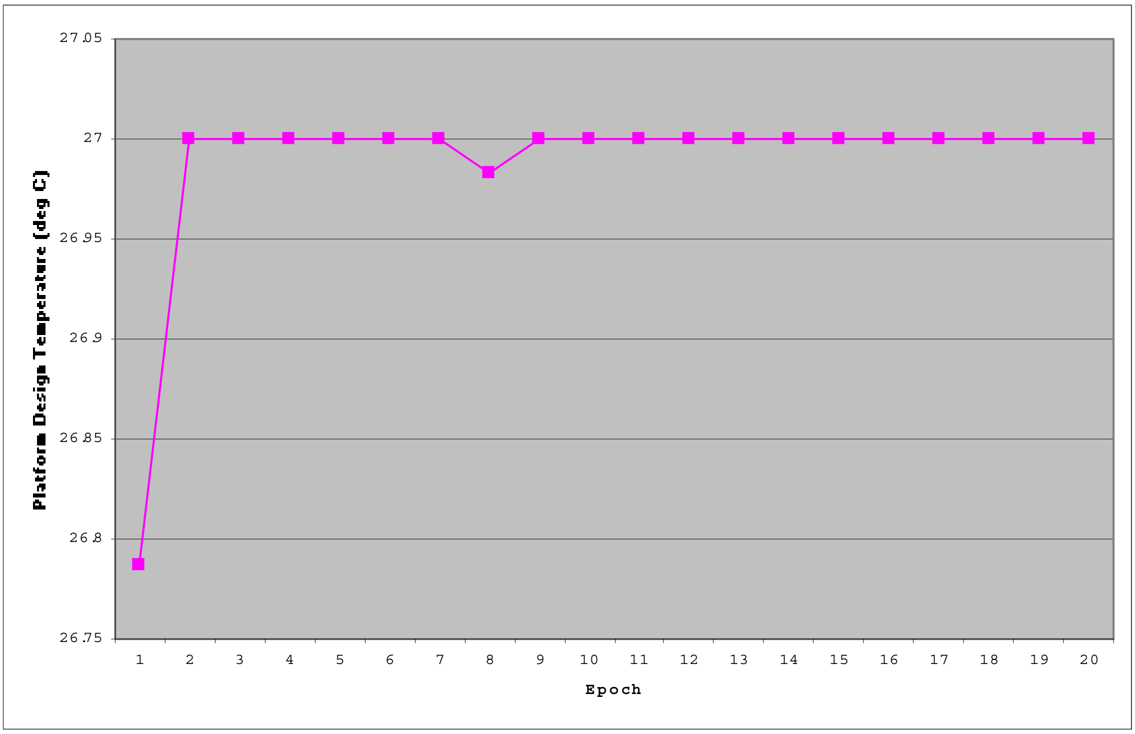

Figure 8: Optimum Platform Design Temperature in Each Epoch

From Figure 6, the minimum year-round energy consumption was found from epoch 11 and there was no significant change thereafter. From this evaluation result, the optimum conditions of T_{cws} and T_p were 7.0 °C and 27.0 °C respectively. As compared to the existing conditions 7.2 °C and 27 °C, the set point of T_{cws} could be further decreased by 0.2 °C and no change was required for T_p. Although the optimization results were close to the existing ones, it indicated that lower T_{cws} could be achieved since the effect of less operation of air side equipment could outweigh the reduced efficiency of chillers during part load situations. In reality, if the optimum conditions were determined by the judgement of the plant operators, there would be a tendency to increase T_{cws} for chillers for saving energy, but ignore the effect from the air side and part load operations. Therefore the EA model provided an effective and numerical mean to determine the optimum conditions, instead of trial-and-error experience and insight.

4.3 Further Applications

The studies were mainly focused on the EMOs of Category I, which was the starting point of energy saving based on the installed equipment and systems. In fact the developed EA optimization and simulation model can also be used to investigate the energy saving potential for different EMOs of Categories II and III, i.e. involving investment and saving return. For example, the existing installations consist of constant speed pumps, saving potential can be determined by changing them to variable speed type. Another idea would be to study the replacement of the 2-speed fans of major air side equipment by variable speed fans. Therefore the current EA optimization and simulation model can be used in handling a variety of different scenarios in performance-based approach for the subway stations.

5.0 CONCLUSION

Although it was common to use simulation in design, it could also be effectively adopted in facilities management, especially to consider different EMOs and to review the current settings of system operation. In this study, plant simulation package was adopted to develop the model of the MVAC systems of subway stations in a holistic approach, with full considerations of their part load operations, in order to determine the year-round energy consumption. Regarding the EA model, it was developed for searching the optimum for different design and operating parameters. Through the coupled EA and simulation model, the optimum chilled water supply temperature and the platform design air temperature were determined. EA was demonstrated to be useful, and it could replace the traditional parametric studies for the HVAC optimization problems.

On the other hand, further development would be focused on a more robust optimization and simulation model, which would be useful for both design and facilities management of the HVAC systems. Especially in the processes of variation and selection, more choice of operators and approaches should be allowed, so that different HVAC problems can be optimized in efficient way. For constraint handling technique, constraints can be introduced by incorporating penalty function, so the fittest individuals can be sought out more easily, and convergence of evaluation can be achieved more quickly. Since plant simulation process is lengthy, more effective variation and selection would reduce the number of running plant simulation, hence the optimization and simulation package can be more useful in different applications.

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