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District Cooling Systems and Individual Cooling Systems: Comparative Analysis and Impacts of Key Factors

ABSTRACT

District cooling systems are used in many areas, especially where the building density is high. However, its efficiency is still quite controversial compared with conventional individual cooling system, especially in China. It is highly necessary to conduct a detailed study and give clear answers when a decision is made between the district cooling system and individual cooling system. Key factors that affect the decision need to be studied. This paper therefore conducts a comprehensive performance assessment of district cooling systems by comparing it with individual cooling systems. The comparative performance of both systems is analysed when the combination of buildings with different functions varies. The optimal combinations for each system are obtained based on Genetic Algorithms and recommendations are summarized for better application of both systems. Impacts of the efficiency of chillers, the resistance of chilled water networks and the cooling load on the comparative performance are quantified considering uncertainties. Based on the analysis and comparison, suggestions are presented for future application of district cooling systems and individual cooling systems.

KEYWORDS

District cooling system; individual cooling system; comparison; building combination; cooling load; uncertainty

1. INTRODUCTION

Building energy systems with high efficiency are urgently required due to energy shortage and increasing requirement on thermal comfort. Among all the energy consumers in buildings, heating, ventilation and air conditioning (HVAC) systems contribute to about 40% of the total energy consumption (EMSD 2014). Efficient cooling systems therefore play an important role in reducing the energy consumption of buildings, especially in cooling dominated areas. District cooling systems (DCSs) are used in many countries such as Sweden, Japan, US, UAE, etc. (Gang et al. 2016), which serve a group of buildings for cooling and dehumidification purposes (ASHRAE 2013). Advantages and applications of district heating and cooling systems are reviewed and summarized in (EMSD 2011; Gang et al. 2016; Rezaie and Rosen 2012).

DCSs are often coupled with district heating systems (Chinese 2008; Erdem et al. 2010; Kato et al. 2008), or combined heat and power (CHP) systems to supply users cooling, heat and power simultaneously, which are combined cooling, heat and power (CCHP) systems (Nagae et al. 2011; Zhu et al. 2008). The CCHP system can achieve high efficiency due to heat recovery measures and cooling production via absorption chillers (Fu et al. 2011). By using communal pipelines with the district heating system and making full use of primary energy resources, DCSs coupled with CHP systems are usually preferred to individual cooling systems (ICSs). Such integrated systems are popular in heating dominated areas (Hart and Rosen 1996; Pak and Suzuki 1997; Rosen et al. 2005) and DCSs serve as supplemental systems to meet the cooling demand of customers. In cooling dominated areas, the application of CCHP systems is not widely reported.

Performance assessment of cooling systems is necessary before the decision is made between DCSs and ICSs for a new district or area (Chan et al. 2006; Chow et al. 2004). Many studies have been done to compare the performance of DCSs with conventional cooling systems and results indicate that DCSs are more efficient (Gang et al. 2015; Pampuri et al. 2016). A district cooling and heating system using sea water heat pumps was compared with a coal-fired heating system & a conventional air conditioning system (Li et al. 2007). Results show that the district cooling and heating system has a lower annual cost, significant energy saving and environmental benefits. Another district cooling and heating system using seawater in the north of China was compared with centrifugal chillers & natural gas-fired boilers, steam-driven lithium bromide absorption chillers & hot water from a nearby power plant, and natural gas-fired lithium bromide absorption heat pump systems. Results indicate that the economic performance of these systems highly depends on the local tariff and policy. To encourage the use of renewable energy (referring to the district cooling and heating system), the policy privileges are very necessary (Shu et al. 2010). Authors of this paper also conducted performance assessment of DCSs by comparing with ICSs (Gang et al. 2015) and results show that the DCS is more energy efficient. From the above review and literatures, it can be found that DCSs have higher efficiency than the conventional ICSs. Many advantages can also be found to explain the priority of DCSs, including the cooling load concentration effect, efficient equipment, easy integration with local renewable energy, etc. (Shimoda et al. 2008).

The DCS should be widely used in China urban areas if it is really energy efficient, where urbanization is developing so rapidly, the building density is high and the requirement for energy saving is so urgent. However, the fact is that the application of DCSs in China is very limited. The conclusion that the DCS is more energy efficient is also quite controversial. Reasons for the party against the application of DCSs mainly include (Zhu et al. 2008): (1) Chilled water pumps of DCSs are very energy consuming. Long distance from the central cooling plant to users makes the DCS very energy consuming due to the chilled water pumps and the corresponding cold loss; (2) Chillers in ICSs can be as efficient as that in DCSs; (3) The low partial load leads to the low efficiency of DCSs. The impacts of these reasons on the comparative performance of DCSs and ICSs need to be quantified and clear answers need to be given to such a controversial system, which are not found yet in existing studies.

In addition, available studies about the performance comparison between DCSs and conventional cooling systems are all based on deterministic results. The cooling load, efficiency of chillers, resistance of chilled water networks, etc. are all determined based on the planning information or experience. However, uncertainties in these key factors will affect the comparative performance. For example, the cooling loads are often over-estimated to ensure sufficient cooling supply when determining the capacity of DCSs and ICSs. Without considering uncertainties, the performance assessment and the impact evaluation of key factors can be not accurate and the decision made from the comparative analysis can be very risky.

This paper therefore attempts to conduct comprehensive assessment and comparative analysis of the performance of DCSs and ICSs. Two objectives are to be achieved: 1) it aims to provide clear answers when the decision is made between DCSs and ICSs in terms of energy consumption; 2) Primary factors affecting the decision are analysed and their impacts considering uncertainties are quantified through sensitivity analysis. Rather than proposing a method or models for DCSs or ICSs, this study aims to address the important but not well handled problems in DCSs: Is the DCS an efficient system? What’s the best situation for application of DCSs and ICSs? What are the key factors to determine its priority over the ICS? These questions will be answered through a case study of a DCS in a new development area of Hong Kong. The impacts of the following factors are investigated considering uncertainties:

- Combinations of buildings with different functions, such as office buildings, commercial malls, hotels, etc.;
- The efficiency of chillers in DCSs and ICSs;
- The cooling loads in the district.
- The resistance of chilled water networks.

The paper is organized as follows. In Section 2, the methodology of this study and factors concerned to compare the performance of DCSs and ICSs are introduced. In Section 3, a DCS in the new development area is introduced. System description and primary models for the DCS and ICSs are presented. In Section 4, the performance of DCSs and ICSs under different combinations of buildings is analysed. In Section 5, comparative performance of both systems under different factors with uncertainties is presented. In Section 6, discussions on the performance of DCSs and ICSs are given. Conclusions and recommendations for future application of DCSs are summarized in Section 7.

2. COMPARATIVE ANALYSIS METHOD AND FACTORS CONCERNED

The method of this study is shown in Fig. 1. According to the planning information from the government, the DCS and ICS can be designed following the local design manual or practice. Both the DCS and ICS can be modelled by building and integrating models of chillers, cooling water pumps, chilled water pumps, cooling towers, etc. With the annual hourly cooling load and the models of the DCS and ICS, the performance of the DCS and ICS can be analysed and compared. Impacts of the building combinations, the efficiency of chillers, the resistance of chilled water systems and cooling loads are quantified considering uncertainties.

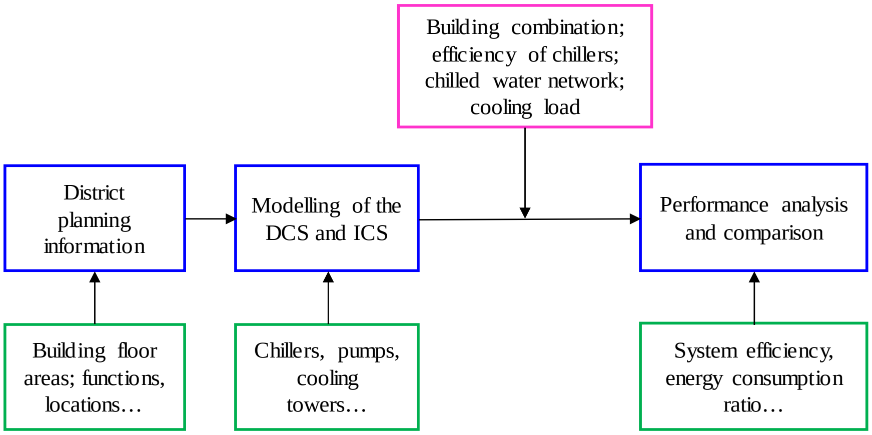


Fig. 1 Method to conduct comparative performance assessment of the DCSs and ICSs

Uncertainty in the combinations of buildings with different functions

Buildings with different functions will be built for a district/community and the floor area percentage (FAP) of each type of buildings can be found from the planning information. However, the actual FAP can be different when the new district is actually constructed, which is taken as uncertainty in the combinations of buildings. The cooling loads (W/m^2) of typical buildings with different functions in a typical summer week are shown in Fig. 2. It can be seen that the cooling load profiles of buildings with different function vary largely. The cooling loads of office buildings and schools are higher during the daytime and lower during the night time. Hotels and residential buildings have higher cooling load during the night time. All the buildings have lower cooling loads at weekdays than that at weekends except commercial malls. By changing the FAPs of different types of buildings, the performance of the DCS and ICS can be obtained and compared. Six types of buildings are considered in this study, including office buildings, hotels, commercial malls, residential buildings, schools and hospitals, as shown in Eq. (1) and Eq. (2). Where, CL is the annual hourly cooling load of the district, $X=[x1,x2,x3,x4,x5,x6]$ is the FAP that each type of buildings occupies and $0=<x1,x2,x3,x4,x5,x6\leq 1$. X is constrained by Eq. (2). $A=[a1,a2,a3,a4,a5,a6]$ refers to the annual hourly cooling load (W/m^2) of different buildings.

$$CL=XA^T \tag{1}$$

$$x1+x2+x3+x4+x5+x6=1 \tag{2}$$

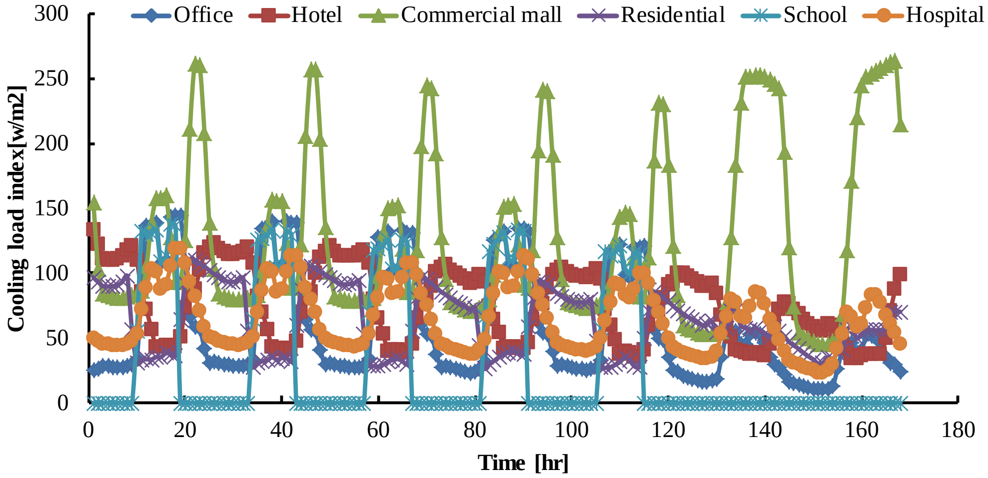


Fig. 2 Cooling loads of six typical buildings in a typical summer week

Two purposes will be achieved by considering the uncertainty in the combinations of buildings. One is to analyze the performance of DCSs and ICSs under different cooling load profiles. The other is to obtain the optimal combination for DCSs and ICSs. To assess the comparative performance of DCSs, an index ECR (energy consumption ratio) is proposed as shown in Eq. (3), which is obtained by dividing the annual energy consumption of DCSs (E_{DCS}) by that of ICSs (E_{ICS}). By changing the FAPs of different buildings, the optimal combination for DCSs can be obtained with the lowest ECR. The optimal combination for ICSs corresponds to the largest ECR. Genetic algorithm (GA) is used to realize the optimization (Davis 1991).

$$ECR=E_{DCS}/E_{ICS} \tag{3}$$

Uncertainty in the efficiency of chillers

Chillers play an important role in energy consumption of both DCSs and ICSs. It is regarded that the efficiency of chillers in DCSs is higher than that in ICSs due to larger capacities. However, with the technology development in chillers, the efficiency of chillers with smaller capacity can also be high. In addition, the capacity of chillers in some ICS can also be very large. The efficiency differential between chillers in DCSs and ICSs may be large or small. This is called the uncertainty in the efficiency of chillers. It is necessary to consider the uncertainty in the efficiency of chillers in DCSs and ICSs when comparing their performance. In this study, the impact of the efficiency of chillers on the comparative performance is quantified by changing the rated COP (coefficient of performance) differential of chillers.

Uncertainty in the resistance of chilled water networks

For the energy consumption of chilled water systems, the main difference between DCSs and ICSs lies in the chilled water system that connects the central cooling plant and the users. The resistance of the chilled water networks is the primary factor that affects the energy consumption. It can be under-estimated or over-estimated, which is taken as the uncertainty in the resistance of chilled water networks. The uncertainty in the resistance of chilled water systems should be taken into account when comparing the performance of DCSs and ICSs. It is quantified by changing the required hydraulic head of chilled water pumps.

Uncertainty in the cooling load

The actual cooling load can be different from the predicted due to uncertainties in the weather, building material and size, indoor heat gain sources (Gang et al. 2015). Even though the prediction is accurate, the cooling demand of the buildings may change in the future time. With the development of green buildings, zero energy buildings or green urban, the cooling load of the district may decrease by using energy-efficient technologies or changing occupants' behavior. It can also be possible that the cooling demand of the entire district rises due to the change of building functions or increase of buildings. Such changes or differences of the cooling loads are taken as uncertainty in the cooling load. When conducting performance assessment, the uncertainty of cooling loads should be taken into account. In this paper, the uncertainty in the cooling load is considered by multiplying the predicted cooling loads with certain factors.

3. A CASE STUDY ON THE DCS OF A NEW DEVELOPMENT AREA

To accommodate increasing population and promote the development of Hong Kong, the government launches a land reclamation program which turns remote mountain areas into new development areas. For the north east new territories of the city, three development areas will be planned including Kwu Tung North new development area, Fanling North new development area and Ping Che/Ta Kwu Ling new development area. Kwu Tung North area is selected to study the performance of DCSs and ICSs. According to planning information from the government, many types of building will be built in these comprehensive development areas, including government buildings, research institutions, hospitals, hotels, metro stations, commercial malls residential buildings, schools, retail shops, etc. Detailed assessment of the DCS by comparing it with ICSs has been conducted by the authors (Gang et al. 2015), which are deterministic results without considering uncertainties in the systems. Further study based on the previous results is conducted in this paper, which involves uncertainties in the factors listed in Section 2.

The sizing of the DCS is based on the annual peak cooling load. Ten identical chillers are selected, together with ten groups of cooling water pumps and chilled water pumps. Each ICS is designed based on the peak cooling load of the individual building. It is assumed that the capacity of an ICS for each type of buildings will not exceed 6000 kW. If the cooling load of some type of buildings is larger than 6000 kW, it will be divided into several individual buildings. Three chillers are designed for each ICS, together with three groups of cooling water pumps and chilled water pumps. The performance of chillers in the DCS and ICS is assumed to follow the similar curve, as shown in Fig. 3. The rated COP of chillers may be different but the curve is similar. The chilled water system is set to be constant flow rate and the energy consumption of pumps is calculated using Eq. 4. Where, H is the pump hydraulic head (m), Q is the water flow rate (m3/s), ρ is the density of the water (kg/m3), g is the gravitational acceleration (m/s^2) and η is the pump efficiency.

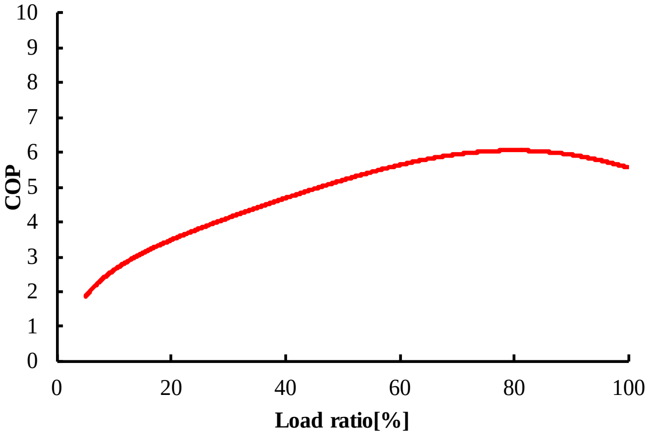


Fig. 3 Performance curve of chillers at different part load ratios

$$N=H*Q*\rho*g/(1000*\eta) \tag{4}$$

4. PERFORMANCE ANALYSIS AND COMPARISON UNDER DIFFERENT COMBINATIONS OF BUILDINGS

Energy consumption of the DCS and ICS under different combinations of buildings is evaluated and ECRs are analysed. The combinations of buildings that are suitable for each system with higher systematic efficiency are presented. Then the optimal combination for each system is obtained by using GA.

4.1. Energy Consumption of the DCS and ICS

The performance of DCSs and ICSs at all the possible combinations of buildings with different functions is evaluated as shown in Fig. 4. The annual average COP is calculated by dividing the annual cumulative cooling load by the energy consumption of the cooling system. The FAP of each type of buildings changes at an interval of 0.1 so totally 2602 trials are conducted. The rated COP of chillers in both DCSs and ICSs is 5.5. Fig. 4 shows that annual average COP of the DCS varies between 3.75 and 4.1 and most of them locate at around 3.8. Only several combinations can obtain very high COPs, which correspond to the combinations that the FAP of schools is high. The FAP of schools is between 80% and 90%. Other buildings (mainly the office buildings and hotels) occupy around between 10% and 20% of the floor areas. No commercial malls or residential buildings are included for these combinations with higher COPs.

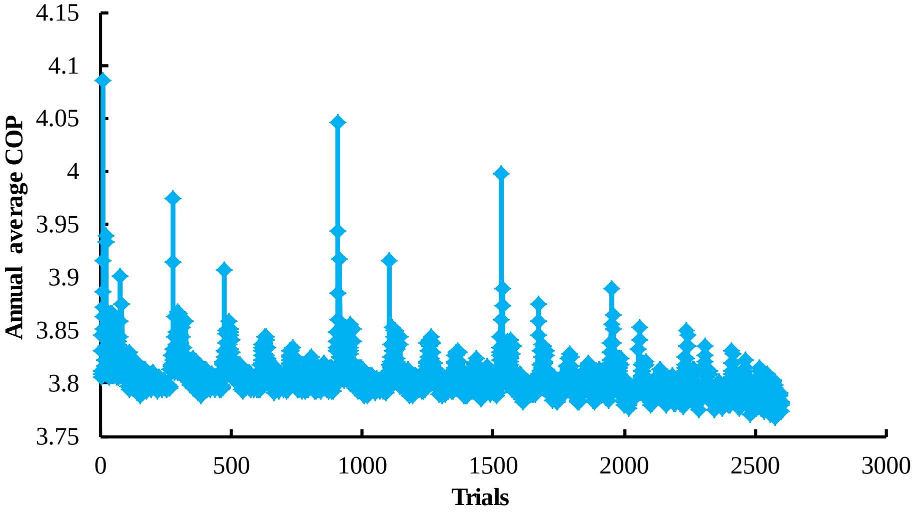


Fig. 4 Annual average COPs of the DCS at different combinations of buildings

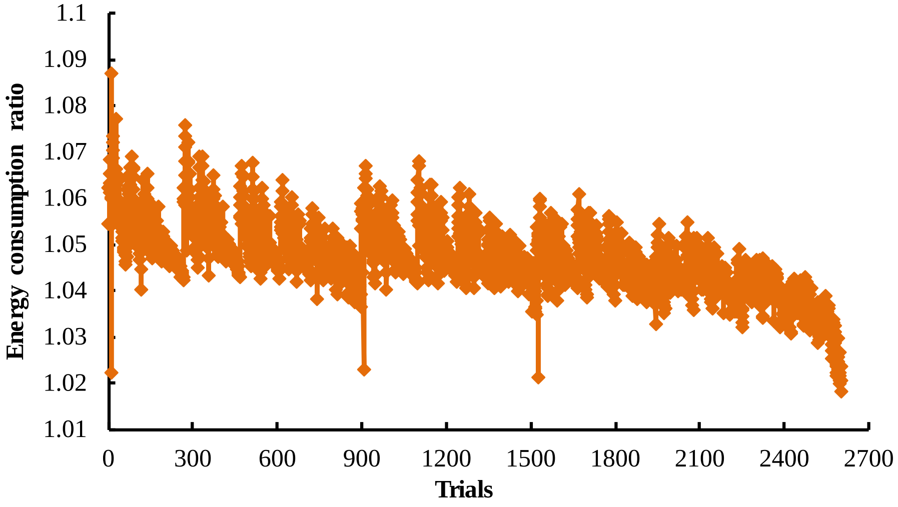


Fig. 5 ECRs under different combinations of buildings

To compare the performance of DCSs and ICSs, ECRs are calculated under different combinations of buildings as shown in Fig. 5. It shows that the ECR is always more than 1, which indicates that the energy consumption of DCSs is always larger than that of ICSs. It demonstrates that when the chillers in ICSs have the similar efficiency as that in DCSs, DCSs are not as efficient as claimed in literatures. The excessive energy consumed by DCSs is between 2% and 9%. The lower ECR corresponds to the combinations with a higher FAP of schools. The highest ECR occurs when the FAP of schools is 100%. It indicates that if all the buildings in the district do not have cooling demand during the night time, both DCSs and ICSs can achieve good performance and the advantage of ICSs is the largest. ICSs should be preferred under such conditions.

Conventional optimization in the combinations of buildings aims to get the highest absolute efficiency of DCSs (Chow et al. 2004). However, a high absolute efficiency of the DCS does not necessarily guarantee a high energy saving potential when being compared with ICSs. That's because the ICSs can also be very efficient at the time, which is proved in results shown in Fig. 5. The relationship between the annual average COPs of DCSs and ECRs is illustrated in Fig. 6. It can be seen that only several combinations with high COPs correspond to low ECRs. Most of the data distribute at the bottom left, where both the ECRs and COPs of the DCSs are low. It indicates that the advantages of DCSs mainly are shown when the efficiency for both DCSs and ICSs is not very high.

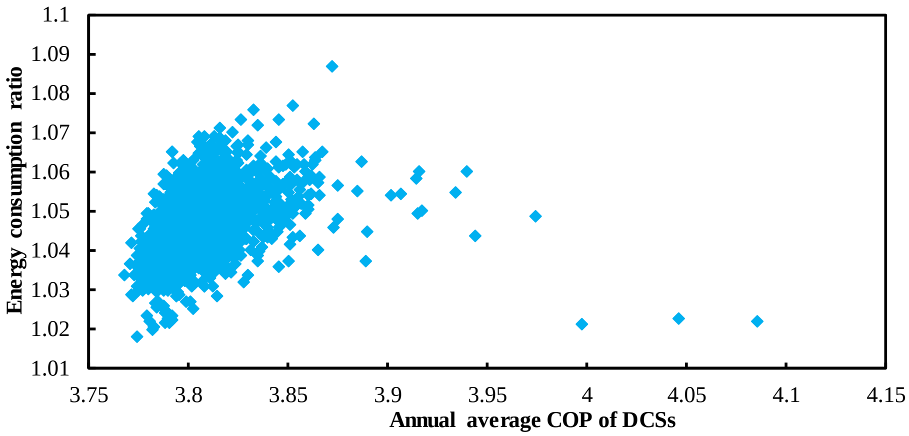


Fig. 6 Annual average COPs of DCSs vs. Energy consumption ratio

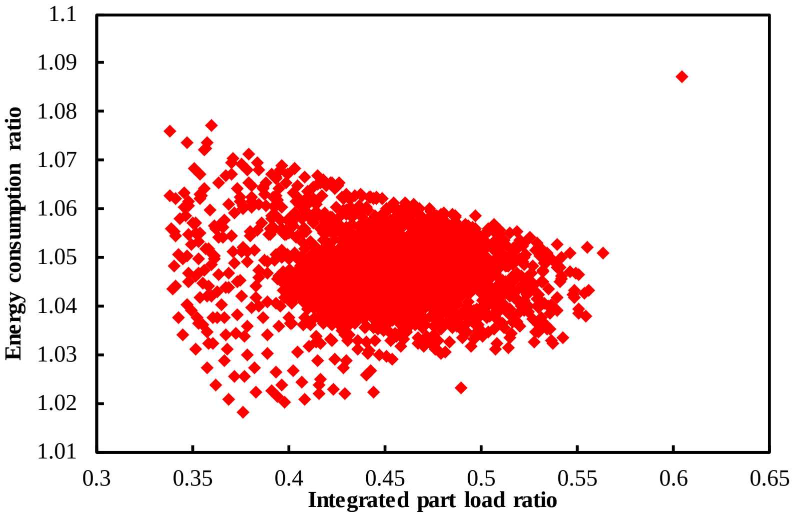


Fig. 7 Energy consumption ratio vs. integrated part load ratio

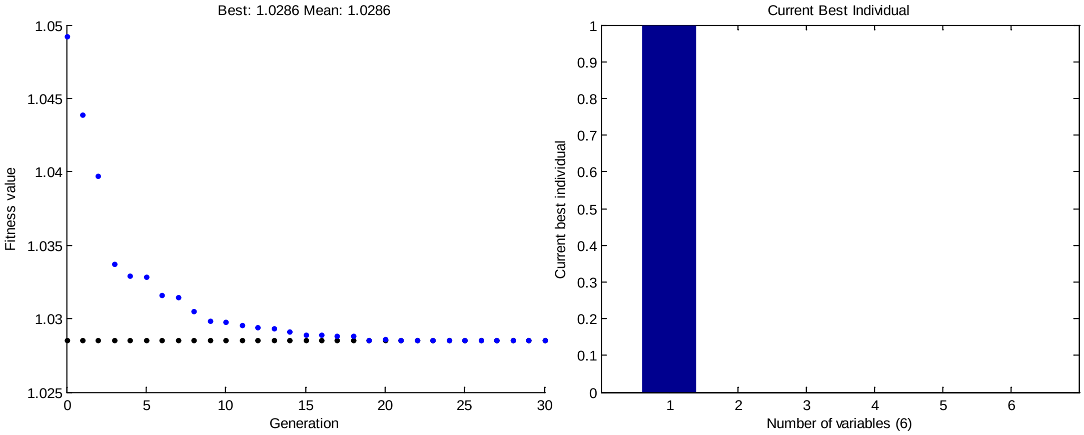
Another parameter is proposed to show the relationship between energy saving potential of DCSs and the cooling load distribution in a year, which is called integrated part load ratio (IPLR) as shown in Eq. (5).

P_i is the part load ratio of the cooling load, which ranges from 0 to 1 with an interval of 0.2. PL_i refers to the percent of time in a year that the part load ratio falls in the range between P_{i-1} and P_i. The relationship between the ECR and IPLR is shown in Fig. 7. It can be seen that when the IPLR is low, the ECR varies largely and it is hard to judge which system is better. With the increase of IPLRs, the variation of ECRs decreases and the comparative results become stable, where ECRs mainly locate between 1.04 and 1.05.

$$IPLR=PL_1\times P_1+PL_2\times P_2+\dots PL_n\times P_n \tag{5}$$

4.2. Optimal Building Combination for DCSs and ICSs

By comparing the performance of DCSs and ICSs, the optimal combination for DCSs or ICSs can be obtained by GA, with the objective of the lowest or highest ECR. The input variables are the FAPs of six types of buildings. The combination with the lowest ECR is the optimal for the DCS and the one with the largest ECR is the optimal for the ICS.

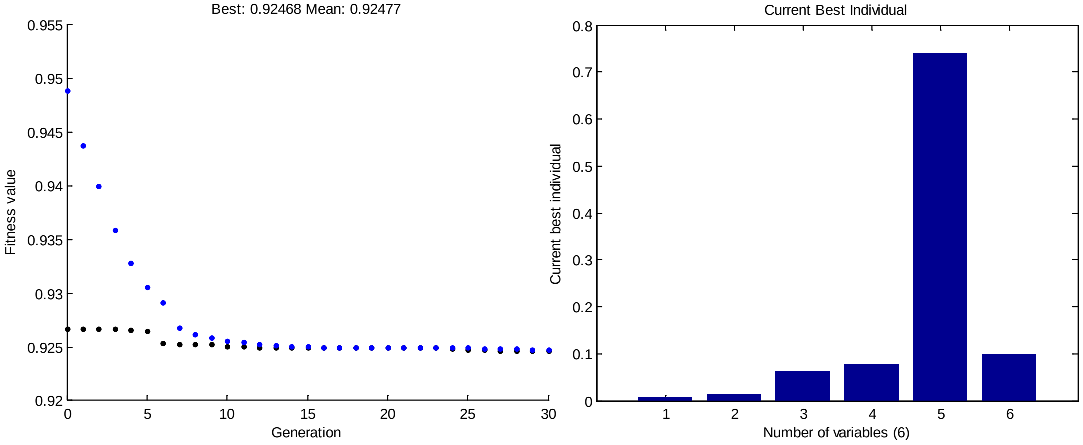


(1-office buildings, 2-hotels, 3-commercial malls, 4-residential buildings, 5-schools, 6-hospitals)

Fig. 8 The optimal combination of buildings for the DCS

The process to get the optimal combination of buildings for the DCS is shown in Fig. 8. It shows that the process converges after 20 generations and the optimal combination for the DCS can be obtained with the lowest ECR of 1.0286. It indicates at least 2.86% more energy will be used by the DCS compared with ICSs. The optimal combination is shown in Fig. 8, where *x1* is 100% and other variables are zero. It means that the advantage of DCSs can be maximized when all the buildings in the new development area are used as office buildings.

The process to get the optimal combination of buildings for ICSs is shown in Fig. 9. It shows that the optimal combination can be obtained after 15 generations with the lowest reciprocal of ECR 0.92 (ECR is 1.09). That indicates that energy consumption of ICSs can be around 9% less than that of DCSs when the chillers in both systems have similar efficiency. The optimal combination for ICSs is shown in Fig. 9, which is X=[0.008,0.013,0.062,0.077,0.74,0.099]. It can be seen that the FAP of schools is very large (74%) among all the buildings. The results are consistent to that in Section 4.1. It indicates that the advantage of ICSs is maximized if most of the buildings have the similar cooling load profile to schools in the district.



(1-office buildings, 2-hotels, 3-commercial malls, 4-residential buildings, 5-schools, 6-hospitals)

Fig. 9 The optimal combination of buildings for ICSs

5. IMPACTS OF KEY FACTORS ON THE COMPARATIVE PERFORMANCE CONSIDERING UNCERTAINTIES

5.1. The Efficiency of Chillers

Chillers are the primary energy consuming components in both DCSs and ICSs. Results in Section 4 show that when the efficiency of chillers in both systems is the same, DCSs have no advantage in terms of energy saving. Usually chillers with a larger capacity have a higher efficiency (a higher rated COP) so the efficiency of chillers in ICSs has a strong possibility to be lower than that in DCSs. A sensitivity study is conducted on the performance of DCSs and ICSs when the efficiency differential of chillers in both systems varies. The rated COP of chillers in ICSs changes from 4.1 to 5.5 at an interval of 0.2 while the rated COP of chillers in the DCS remains constant as 5.5. The ECRs at different combinations of buildings are shown in Fig. 10.

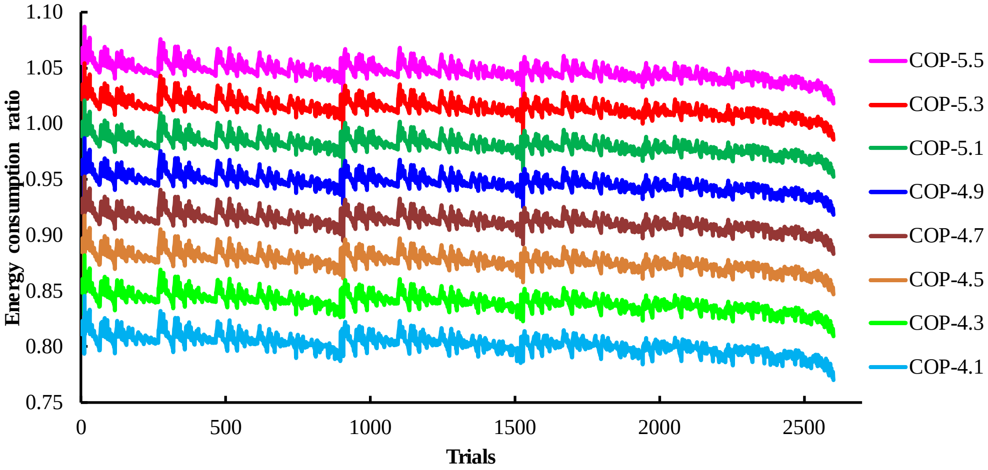


Fig. 10 ECRs at different rated COPs of chillers in ICSs

From Fig. 10 it can be seen that the efficiency of chillers plays an important role in the comparative performance. The ECR decreases significantly when the rated COPs of chillers in ICSs become lower. When the rated COP of chillers is 5.3, only several combinations of buildings have an ECR less than 1. It indicates that DCSs can be more energy efficient than ICSs once the chillers in DCSs have a higher efficiency. Almost all the ECRs at different combinations of buildings are less than 1 when the rated COP of chillers in ICSs is 5.1. When the rated COP of chillers in ICSs is 4.1, more than 20% of energy can be saved by DCSs. It demonstrates that the efficiency of chillers is very important to determine the priority of DCSs to ICSs. When selecting DCSs or ICSs, ICSs are recommended if the chillers in ICSs are also very efficient. Otherwise, DCSs should be recommended.

5.2. The Resistance of Chilled Water Networks

Chilled water systems in DCSs consume much more energy than that in ICSs. The key way for the DCS to be more efficient is to cover the excessive energy used by chilled water systems with the energy saved by other components. The pre-assumed required hydraulic pump head is 40m and it changes from 30m to 60m with an interval of 5m in the uncertainty analysis. The rated COP for chillers in both DCSs and ICSs is 5.5. The ECRs at different resistances are shown in Fig. 11. It shows that the ECR becomes larger with the increase of resistance. By increasing the resistance from 30m to 60m, the ECR rises from 1 to 1.14. The ECR is always over 1, which indicates that the DCS is always more energy consuming. It demonstrates that if the efficiency of chillers in both systems are similar, DCSs cannot be more energy efficient than ICSs, no matter how the resistance of chilled water networks and the combination of buildings change.

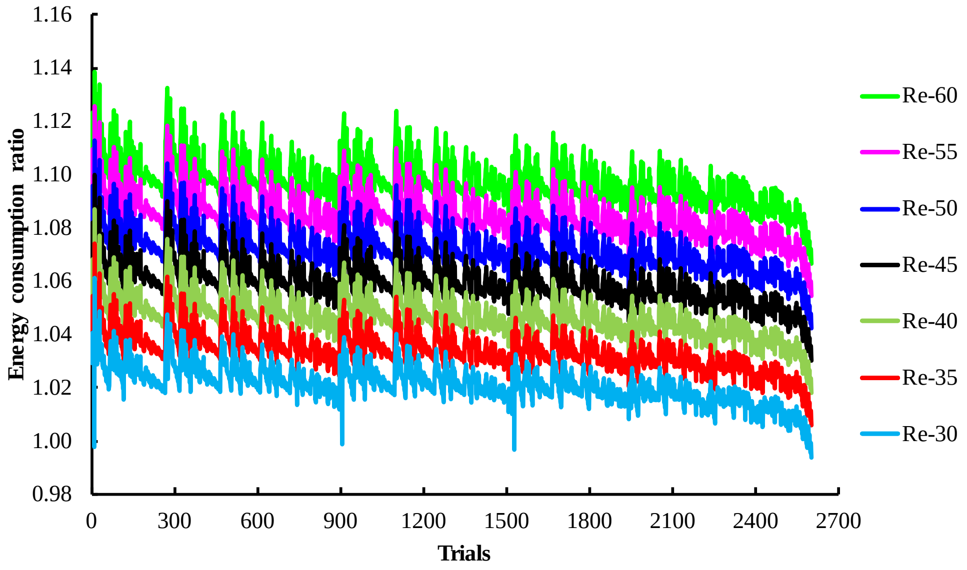


Fig. 11 ECRs vs. Resistances of chilled water networks

5.3. The Cooling Loads

The ECRs for every combination of buildings are shown in Fig. 12, considering uncertainty in the cooling load of buildings in the district. A factor ranging from 0.5 to 1.5 is assigned to the cooling loads obtained without considering uncertainty. The rated COPs of chillers in DCSs and ICSs are the same, which are 5.5. As shown in Fig. 12, when the cooling loads (the factor) increase, the ECR increases, indicating that the DCS is more energy consuming compared with ICSs. The advantage of DCSs will be reduced if the cooling load in the new area keeps increasing. The ECRs are always larger than 1 and can be high up to 2 when the factor is over 0.9. When the cooling load become 50% less than the estimated, the ECR can be low to 0.88. It means that the DCS can be more energy efficient if the cooling loads decrease due to green technologies or are over-estimated.

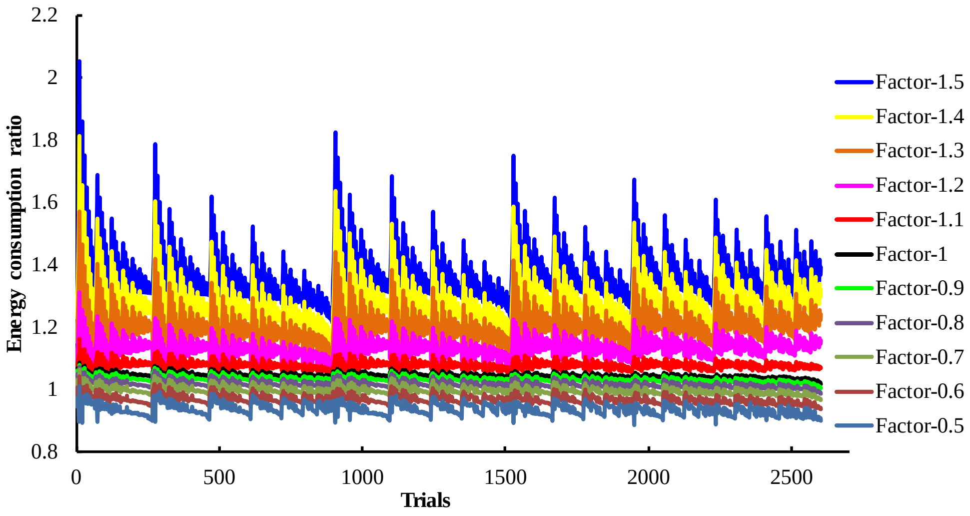


Fig. 12 ECRs at different combinations considering uncertainties in the cooling load

6. DISCUSSIONS ON THE COMPARISON, ASSESSMENT AND APPLICATION OF DCSS

The DCS is regarded as an efficient alternative in many available literatures. However, its application in China is very limited and the conclusion that it is efficient is also controversial. No or little measurement data can be found to show the actual performance of DCSs. Only several reports or news show that the high cooling price usually drives the users to terminate the connection with DCSs and to install ICSs. The cooling price of DCSs can be as high as the local electricity price while the cooling price of ICSs is only one third of the electricity price. However, a high cooling price cannot be taken as a proof of low efficiency of the DCS. The high price can result from the management problem related to the operators and investors who concern he profits rather than the energy saving or pollution emissions. With such background, this paper attempts to find out the facts about the efficiency of DCSs by presenting quantitative comparison in terms of energy consumption. The index to evaluate the performance of DCSs should be selected carefully. Sometimes the annual average energy consumption (kWh/m^2) is used. It is very risky and doubtable to use this index without considering the cumulative cooling supply time, even if the climate or function of buildings may be similar. For example, an office building with 12 opening hours per working day can have much higher energy consumption per year than another office building, which locates in the same city but only has 10 opening hours per working day.

The area selected in this paper locates in Hong Kong, which is a city with a high density of high-rise buildings and the cooling demand is large due to the subtropical area. The application of DCSs in European countries is very wide. One reason is that DCSs share the same pipelines with district heating systems so that not too much additional capital cost is required. If only cooling is required by buildings, the capital cost and installation cost are another very important factors besides energy consumption to be considered when selecting between the DCS and ICS.

The chilled water system in the DCSs of this paper is assumed to be constant flow-rate. This is not often used in DCSs and may affect the conclusion. However, from the sensitivity study on the chilled water network resistance, it can be found that even the energy consumption of chilled water systems is reduced by 25%, the DCS is still hard to be more efficient. It can be deduced that the energy saving by DCSs is still not promising even if the chilled water system is variable flow rate when chillers in ICSs have similar efficiency to that in DCSs.

This study investigates both the absolute and comparative performance of DCSs and ICSs at all possible combinations of building with different functions. One opinion presented by this paper is that the absolute performance of DCSs or ICSs determines that whether the system can be efficient. The comparative performance determines that whether the system is a right choice compared with other options. The comparative performance should be accounted and assessed before the decision is made. From the comparison in this study, it can be seen that DCSs and ICSs has their special application situations.

7. CONCLUSIONS

Performance assessment of DCSs compared with conventional ICSs is conducted. Key factors that affect the comparative performance and their impacts are analyzed. Energy consumption ratio is used to indicate the comparative performance of DCSs. By varying the building combinations, rated COPs of chillers, chilled water network resistances and cooling load predictions, the following conclusions can be obtained:

1) The efficiency of DCSs can vary largely by changing the combinations of buildings with different functions. The system COP can vary between 3.75 and 4.1. When the schools, which have no cooling demand during the night time, occupy a high percent of floor areas, the efficiency of DCSs is higher.
2) A high absolute efficiency of DCSs does not indicate the priority of DCSs over ICSs. The advantage of DCSs can be maximized when all the buildings are used as office buildings. The advantage of ICSs can be maximized when the schools have a high share of floor areas among all the buildings

3) When the chillers in both DCSs and ICSs have similar efficiency, the DCSs is more energy consuming. Chillers with higher efficiency should be adopted in DCSs if the priority of DCSs needs to be guaranteed.
4) Larger resistance of chilled water systems will reduce the advantage of DCSs in terms of energy consumption. The cooling load can affect the comparative performance of DCSs. When the cooling load is overestimated or reduced in the future, DCSs have the potential to be more efficient.

Without appropriate design and control, the cooling system cannot achieve its optimal performance and show its advantages, no matter how efficient the system is. Due to the development of smart grid and smart energy supply network, the DCS can be favored and its application will become wider. However, available research on the design optimization of DCSs is not sufficient, which should be improved in the future. This paper can serve as a basis by presenting the comparative energy performance of DCSs.

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