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RESEARCH ARTICLE

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# Design and control optimization of energy systems of smart buildings today and in the near future



**Abstract** Buildings contribute to a major part of energy consumption in urban areas, especially in areas like Hong Kong which is full of high-rise buildings. Smart buildings with high efficiency can reduce the energy consumption largely and help achieve green cities or smart cities. Design and control optimization of building energy systems therefore plays a significant role to obtain the optimal performance. This paper introduces a general methodology for the design and control optimization of building energy systems in the life cycle. When the design scheme of building energy systems is optimized, primary steps and related issues are introduced. To improve the operation performance, the optimal control strategies that can be used by different systems are presented and key issues are discussed. To demonstrate the effect of the methods, the energy system of a high-rise building is introduced. The design on the chilled water pump system and cooling towers is improved. The control strategies for chillers, pumps and fresh air systems are optimized. The energy saving and cost from the design and control optimization methods are analyzed. The presented methodology will provide users and stakeholders an effective approach to improve the energy efficiency of building energy systems and promote the development of smart buildings and smart cities.

**Keywords** Design optimization, Optimal control, Smart building, Energy efficiency

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## 1 Introduction

The energy consumption of buildings is increasing significantly due to the development of the society, the population growth and the high requirement on the indoor thermal comfort. Generally, the energy consumed by buildings is about 40% of the whole society (Omer, 2008). In US, buildings can occupy about 75% of total electricity usage in 2010 (DOE). In China, the primary energy consumption of buildings is around 30% of the total primary energy and around 45% of the electricity. The percentage is much higher in Hong Kong, where is full of high-rise buildings. In Hong Kong, due to the high density of buildings and population, the electricity consumption of buildings in 2015 occuppies more than 90% of the total electricity usage. The electricity used by space air conditioning systems (mainly cooling ) occupies more than 50% of building electricity usage as shown in Fig. 1 (EMSD 2015). Therefore, in order to reduce the energy consumption and $CO_2$ emission of the whole society, it's very important to build energy systems with high efficiency , which will also promote the development of smart cities.

Smart buildings are defined as those '*address both intelligence and sustainability issues by utilising computer andintelligent technologies to achieve the optimal combinations of overall comfort level and energy consumption*' (Buckman et al., 2014). Energy efficiency is an important feature of smart builidngs. Generally, three ways can be used to achieve smart buildings with low energy consumption and high smartness, which are explained as follows:

1) *Decreasing the heating loads and cooling loads by improving the design of buildings.* The heating and cooling loads refer to the required heat to be added to or removed from the building to maintain the indoor thermal comfort at a predefined level. If the heating and cooling loads are decreased, the energy consumption by the building energy systems will accordingly be reduced. The heating and

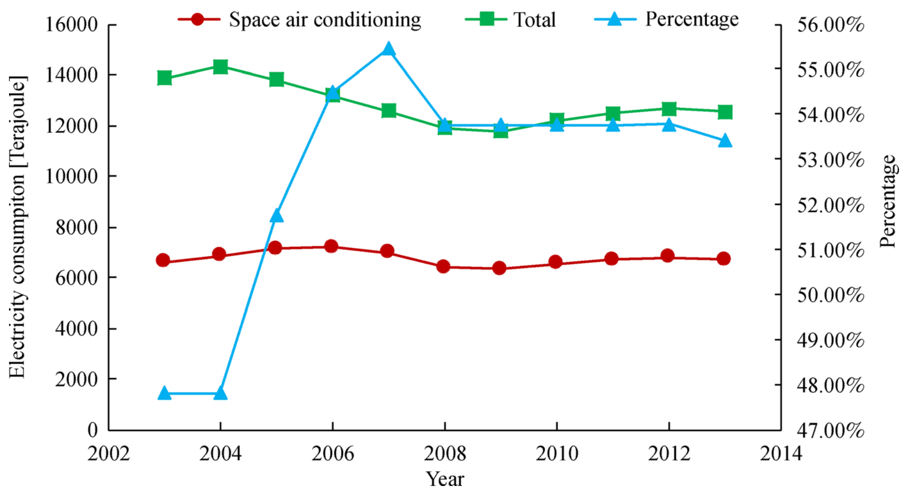


**Fig. 1** Statistic data on the electricity consumption of office buildings and their space air conditioning from 2003 to 2013 in Hong Kong

cooling loads mainly are determined by factors such as the outdoor weather conditions, the building design (building envelope material, windows, orientation, etc.), indoor heat sources (lighting, occupants, plug-in equipment, etc.) and indoor temperature/humidity set-points. To reduce the cooling and heating load, the building envelope can be optimized and carefully selected. For instance, the thick wall or the wall with a lower overall heat transfer coefficient can significantly decrease the heat exchange between the indoor environment and outdoor air. Passive design is often used in the optimization of building envelopes, which is performed at the planning and design stage. The energy performance of buildings using various wall materials, window materials, shielding, orientations, etc., can be assessed by simulating the building via professional software tools such as EnergyPlus (DOE, 2017), TRNSYS (TRNSYS, 2017). By compromising the energy performance, costs or other indices, appropriate material and design of the building envelopes can be determined.

2) *Using equipment and technologies with high energy efficiency*. By using energy efficient equipment and technologies in building energy systems, the thermal requirement of customers can be met with lower energy consumption. Energy efficient equipment refer to the equipment such as the heat pumps, pumps, air handling units (AHUs) and fans, which have higher energy efficiencies than the traditional alternatives. For instance, a water-cooled chiller is usually more energy efficient than an air-cooled chiller. Energy efficient technologies refer to the advanced techniques that can have similar functions but consume less energy (i.e. liquid desiccant technology and ground source heat-pumps). The energy efficiency of the building energy system can be apparently improved by selecting and using energy efficient equipment and technologies.

3) *Optimizing the control and operation of building energy systems*. Appropriate control can reduce the energy consumption of building energy systems through the life cycle. The building energy systems usually consist of many sub-systems and components. All these sub-systems can only work with high efficiency under approriate configuraiton of the systems, proper integration and optimal control.

The design optimization and optimal control of building energy systems is therefore very significant (while the building design is out of the scope of experts in HVAC fields), especially when the development of smart cities and smart grid is so demanding. About 20%–50% of energy savings can be achieved via design optimization and optimal control (Claridge et al., 1994; Haberl et al., 1994). The design and control optimization will not only improve the energy efficiency of building energy systems, but also enhance the smartness of buildings. It will also provide a solid foundation for the buildings to be integrated with smart grid. This paper therefore presents a general methodology for the design and control optimization of building energy systems according to the authors' experiences, which can be generalized to achieve smart buildings. Methods and associated technologies for the design and control optimization are introduced in Section 2. The application of these methods in a new building is introduced in Section 3. The effects of the methodology are introduced in Section 4, followed by conclusions in Section 5.

## 2 Design optimization and optimal control methods of building energy systems

The methodology mainly contains two part: the system design optimization and system control optimization. The design optimization (as shown in Fig. 2) includes three steps: the design commissioning to avoid obviously improper design, the design optimization to obtain the optimal design, and design optimization evaluation. The control optimization mainly has two steps: the development of optimal control and the performance evaluation of the optimal control. Associated technologies and methods in each category are introduced in detail as follows.

### 2.1 Design optimization of building energy systems

The design optimization aims to achieve energy-efficient and cost-effective design scheme, which is the basis on which the building energy system would operate with a high efficiency under most of the conditions, especially when the cooling or heating load is low. The obtained design should also have the ability to accommodate the uncertainties arising from the design process. The major optimization work contains:

- Optimizing the capacity of building energy systems. The capacity of building energy systems should be carefully determined. The oversized systems will lead to more energy consumption and investment costs. The undersized systems will not be able to meet the thermal comfort of users. The capacity should be appropriately determined based on detailed and accurate prediction of the heating and cooling loads, the resistance of the water pipelines, the pressure drop though the air ducts, etc. The sizing includes the number and capacity of chillers, cooling water pumps, chilled water pumps, cooling towers, the ducts, pipelines, AHUs, etc.
- Optimizing the component selection and system configurations. It includes the selection of components with higher efficiency (i.e. water-cooled chillers), the configuration optimization of chilled water network systems (primary variable, primary constant & secondary variable, primary constant only), the combination of large and small chillers and pumps, the connection of cooling towers using communal headers or in parallel, the serial or parallel connection of pumps or chillers, etc.
- Optimizing the selection of advanced technologies. It includes the selection of technologies with higher efficiency such as liquid desiccant technology, the integration with renewable energy, the re-use of waste heat, heat recovery technology and thermal storage, etc.
- Design optimization for adaptive balancing and commissioning. This refers to optimize the design of building energy systems considering uncertainties. The optimal design will maintain good performance not only under the design condition, but also under possible deviations, failures or unpredicted changes. Uncertainty quantification should be conducted and integrated into the design process at the design stage (Gang et al., 2015, 2016).

The energy performance of the optimized design would be evaluated using the developed simulation platform based on the design information. The improper design alternatives and corresponding energy waste would be found and eliminated. At the same time, the performance of optimal design scheme will also be obtained and compared with the original design. The benefits (energy saving, cost saving and $CO_2$ emission reduction) will also be obtained.

### 2.2 Control optimization of building energy systems

By implementing the optimal control strategies, the building energy system would always work at optimal energy efficiency, particularly under partial cooling or heating loads. Two primary steps should be considered in order to obtain the optimal control and operation strategy: 1) Developing optimal control strategies for the chillers, chilled water systems, cooling towers and air systems; 2) Testing the strategies and evaluating the performance of these optimal control strategies in the virtual test platform prior to their real application.

The optimal control strategies that are proposed by the authors' team and have been implemented in real buildings include:

- Global optimization of cooling tower systems (Ma et al., 2009);
- Optimization on the speed control of water pumps distributing water to terminals units (Ma and Wang, 2009);
- Robust sequence control of chillers (Sun et al., 2009);
- Global optimal control of chilled water systems (Ma and Wang, 2009);

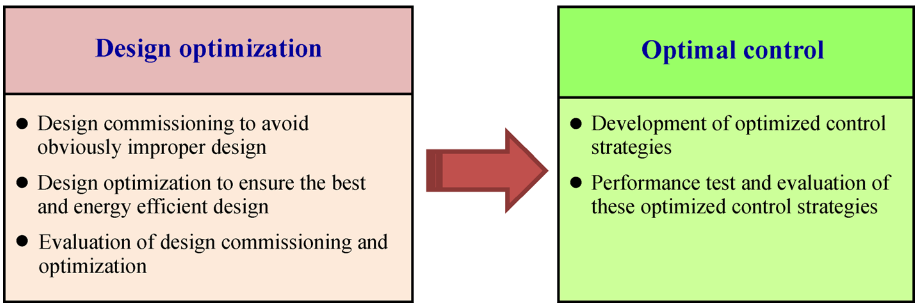


**Fig. 2** Primary steps for design optimization and optimal control

• Model-based optimal control of chiller start (Sun et al., 2010);
• Optimal speed control of water pumps distributing water to heat exchangers (Wang and Ma, 2010);
• Flow-limiting control strategy (Gao et al., 2011);
• Control strategy of ventilation for multi-zone air-conditioning systems (Sun et al., 2011);
• Optimal sequence control of intermediate heat exchangers (Wang et al., 2013);
• Optimization of supply water temperature set-points at secondary side of plate heat exchangers;
• Reset of static pressure set-points;
• Reset of supply air temperature set-points.

## 3 Introduction on a new building and its cooling system for case study

A commercial building and its cooling system is introduced in this section to demonstrate the effects and necessity to implement design optimization and optimal control. The selected building is International Commerce Centre (ICC). Currently the building is the landmark and the tallest building in Hong Kong (Fig. 3). It has 118 storeys and a height of 490 m. The gross floor area is approximately 321,000 $m^2$ excluding the hotel at the top of the building. ICC serves as a commerce center and it has commercial offices, restaurants, shopping arcades, retails and two six-star hotels.

A central cooling system is designed to supply cooling to the whole building. The schematic diagram of the central cooling system is shown in Fig. 4. The cooling plant consists of six identical centrifugal chillers, six cooling water pumps and 11 indoor cooling towers. The individual capacity of the cihllers is 7230 kW and the motor power of each indoor cooling tower is 150 kW. Plate heat exchangers are employed to deliver cooling from the low floors to the high floors to avoid extremely high static pressure. The chilled water system is primary constant and secondary variable flowrate. Each chiller is assigned with a constant-speed condenser water pump and a constant-speed primary chilled water pump. All pumps in the secondary chilled water distribution system are equipped with variable frequency drivers (VFD) except that the primary chilled water pumps for the heat exchangers in Zones 3 and 4 are constant speed pumps. Two AHU systems involving variable air volume (VAV) boxes are installed on each floor serving as offices in this building. To address the winter plume problems, two different types of evaporating cooling towers (named CTA tower and CTB tower, respectively) are used in this building.

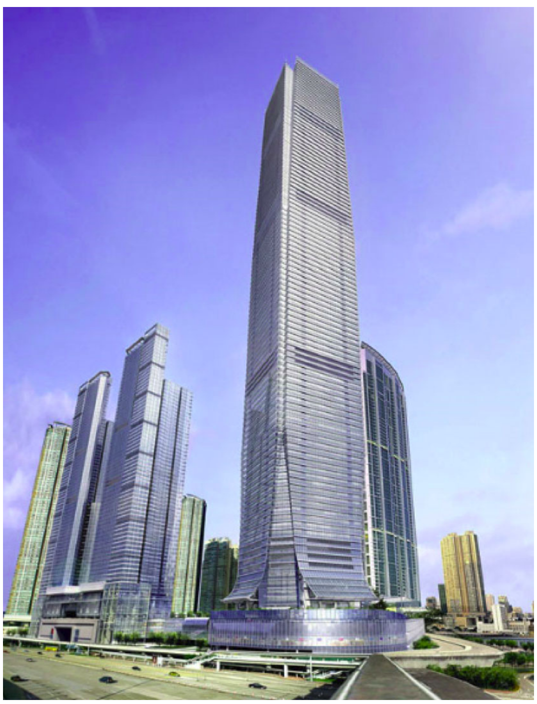

**Fig. 3** The International Commerce Centre (ICC) (http://www.shkp-icc.com/website/showGeneralContent.do#)

The design of HVAC systems of this building began at 2005 and the first stage was finished in 2008. The authors' team, working with the consultants, the developers, the facility management team and the contractors, have made serious efforts to optimize the design and control aiming to improve the performance of the HVAC systems. The authors' team has developed innovative solutions to improve the energy efficiency and environmental performance of building energy systems. The original design of the central cooling plant is revised. The control strategies of the central cooling plant for normal operation and system maintenance are optimized. Energy saving resulting from the design optimization and optimal control are introduced as follows.

## 4 Energy saving resulting from the design optimization and optimal control

The aim of the design and control optimization is to provide the required thermal environment by using much less energy. For the central cooling plant of ICC, the design of chilled water systems and cooling towers are optimized. Control strategies are proposed and implemented on almost all the sub-systems.

### 4.1 Design optimization on chilled water systems and cooling towers

#### 4.1.1 Design optimization of the chilled water systems

In the original design, pumps with constant speeds were proposed at the secondary side of each heat exchanger,

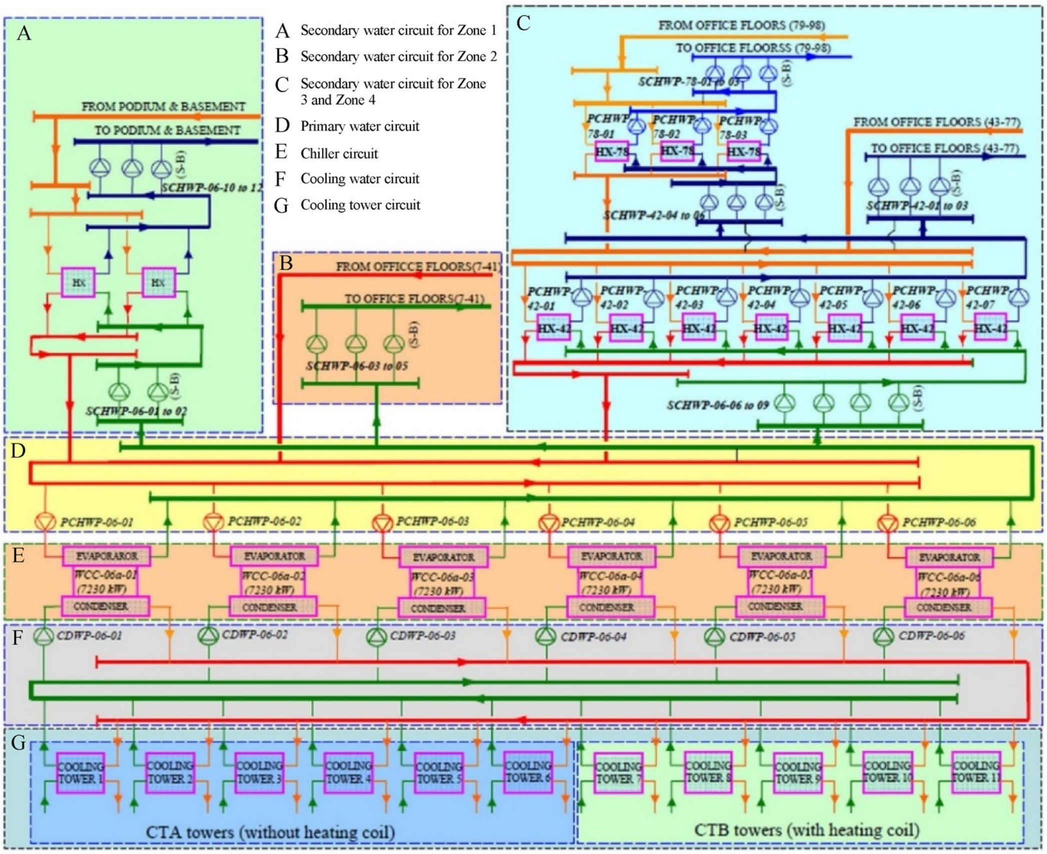


**Fig. 4** Layout of the central cooling system for ICC

which served the upper part of the building (3rd/4th zones). These pumps were mainly used to provide the circulation pressure to overcome the resistance when the chilled water passed through the plate heat exchangers. When the cooling load is low, especially during the night time, the energy consumption of these primary chilled water pumps would contribute to a large portion of the total energy usage in 3rd/4th zones. The author suggested to improve

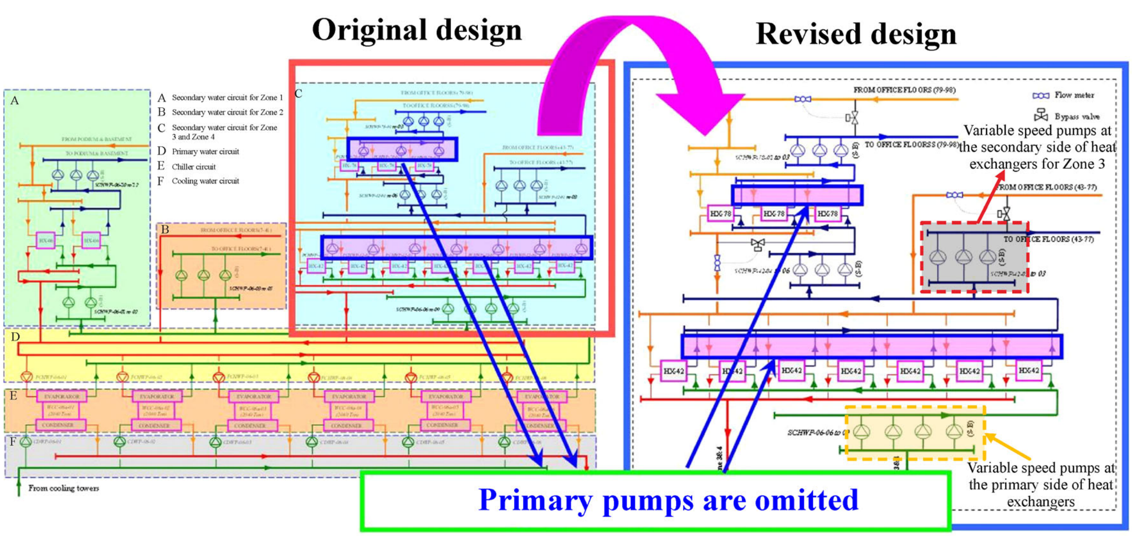


**Fig. 5** Layout of the secondary chilled water loop systems in Zones 3 and 4

the design by eliminating these primary constant speed pumps as shown in Fig. 5 (Ma et al., 2008). The energy consumption and capital cost resulting from the installation of these pumps will be avoided. The on-site tests show that the energy consumption of the variable speed pumps for Zone 3 is slightly increased but the energy saving of the pump system is quite promising. By optimizing the design of chilled water systems, the total energy consumption of chilled water pumps is reduced by about 55% and the annual energy saving resulting from this revised design is over 1.0 M kWh.

#### 4.1.2 Optimization of cooling tower systems by proper selection and operation

Cooling towers using two-speed (two-stage) fans were used in the original design. Actually more energy efficient technologies can be used. Therefore, the design of the cooling tower system is optimized by replacing the two-stage fans with variable speed fans. In the original design, the minimum allowed frequency of the fan is 37 Hz. In the optimized design, the minimum operating frequency of the fan is decreased from 37 Hz to 20 Hz. According to the commissioning test results, the use of variable speed fans and the decrease of minimum operating frequency provide an annual energy saving of up to 2.36 M kWh.

### 4.2 Optimal control for the chillers, chilled water systems and air supply systems

Many optimal control methods have been developed by the authors' team: the robust sequence control of chillers, the optimal control of cooling towers, optimal control of the secondary chilled water pumps, model-based outdoor air ventilation control, indoor air quality and thermal comfort, flow-limiting control to eliminate deficit flow, avoiding low delta-T syndrome and saving pump energy (Gao et al., 2011), optimization of chilled water supply temperature, AHU supply air temperature optimization (Ma and Wang, 2009), differential pressure set-point optimization in the secondary pumps (Ma, 2008). Several of them are introduced as follows.

#### 4.2.1 Robust chiller sequencing control

The sequence control of chillers is important for the energy performance of the whole cooling systems. The conventional method is to determine the operating number of chillers required according to the measured cooling load of buildings. The problem is that the direct measurement of the building cooling load could be unreliable or inaccurate because there are uncertainties associated with the measurement instrument. Therefore, an improved control strategy is proposed by using data fusion to improve the measurement reliability of building cooling load, as shown in Fig. 6 (Sun et al., 2009). This also would provide more confidence in the fused load measurement for robust control and fault detection. The advantages of indirect measurement and direct measurement are combined in the final fused cooling load measurement. The on-site test results show that the improved control strategy can reduce the chiller switches by about half. More than 1% (680,000 kWh per year) energy consumption can be saved in the chiller plant. In addition, chillers can have a longer service time due to less switches.

#### 4.2.2 Control optimization of the secondary water pumps

The conventional control is to use the modulating valves to keep a pressure differential for the secondary chilled water

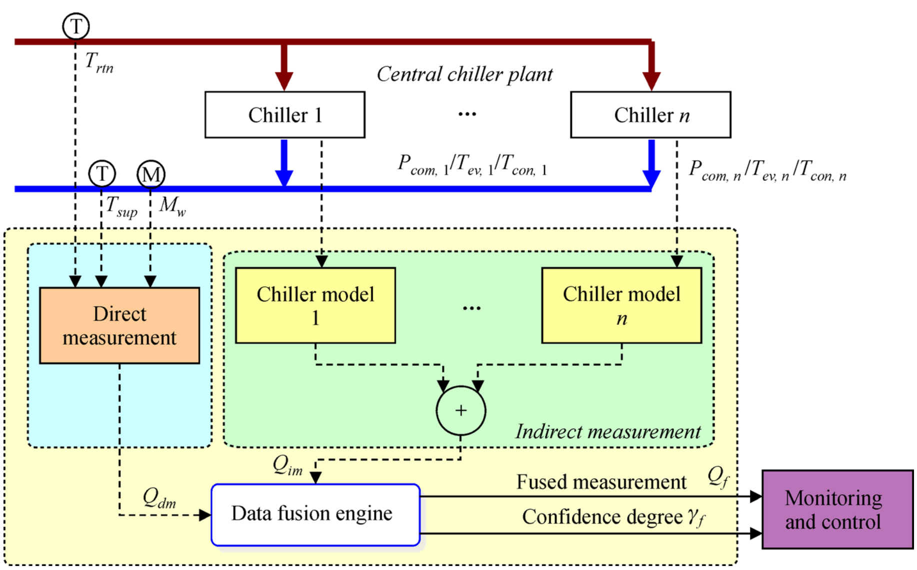


**Fig. 6** Optimized control diagram for the chillers

pumps. The author proposed a new control method, known as a cascade controller, to control the operating speeds of pumps, which are used to distribute chilled water to plate heat exchangers (Wang and Ma, 2009). By fully opening the valve in the cascade control., the pressure drop can be minimized and the energy consumed by pumps can be reduced. The in-situ tests show that the optimized control strategy of chilled water pumps can save the energy up to 250,000 kWh annually.

#### 4.2.3 Optimal control of cooling towers

A hybrid quick search (HQS) method (Ma et al., 2009) has been developed to minimize the power consumption of chillers and fans of the cooling towers. This is especially beneficial under partial loads. The operating number of cooling towers and the water temperature entering the condensers are continuously determined according to system working conditions and weather conditions. The in-situ test show that the improved method can achieve a 1%–4% energy saving.

#### 4.2.4 Indoor air quality and thermal comfort

For the zones served as office areas, individual AHUs are used to provide cooled air to variable air volume (VAV) boxes installed in different zones. Based on ASHRAE standard 62.1, an improved and robust control method, demand controlled ventilation (DCV), for multi-zone office floors is developed and implemented (Sun et al., 2011). This method determines the required fresh air according to the prediction of the real-time occupancy. When the demand of fresh air is quite low, this DCV method can reduce the energy consumption significantly by decreasing the air flowrate. In-situ test results of one typical office floor area show that the proposed method can always achieve a good quality of indoor air. Figure 7 shows that the $CO_2$ concentrations of zones can always be less than 800 ppm, indicating a good indoor air quality.

### 4.3 Energy saving of the whole building

The effects of implementing desing optimization and optimal control proposed by authors can be seen in Fig. 8. Due to the design optimization and optimal control, the energy consumption decreases gradually from 2012 to 2015. One fact is that the average outdoor air temperature in 2015 was 0.7°C higher than that in 2014 and the energy consumption should have been higher. It indicates that the actual energy saving is larger than the monitored energy consumption differential.

The actual energy performance of ICC is analyzed and compared with the baseline performance based on ASHRAE 90.1-2007. The results are summarized in Table 1. It shows that the energy use intensity (EUI) of this building is 182.5 kWh/(m$^2$·year). It can achieve an energy saving of about 30% compared with the baseline performance, where the EUI is 261.4 kWh/ (m$^2$·year). The EUI of ICC in 2012 is 164.5 kWh/(m$^2$·year). Compared with the baseline performance, the energy saving of this building can be 37.1%, which is very promising.

The cost is also evaluated according to the tariff of Hong Kong. Compared with the baseline case based on ASHRAE 90.1, the design and control optimization can lead to an annual cost saving of about 30 M (million) HKD. Compared with the performance of the original HVAC system design and conventional control strategies, the yearly cost saving of ICC can be about 7 M HKD by implementing the life-cycle commissioning and design optimization. Furthermore, no additional investment is required in order to implement the HVAC system design optimization. To apply the developed optimal control strategies, extra investment on hardware has to be made, which is about 2 M HKD. At the same time, another 3 M HKD has to be paid for the manpower when implementing

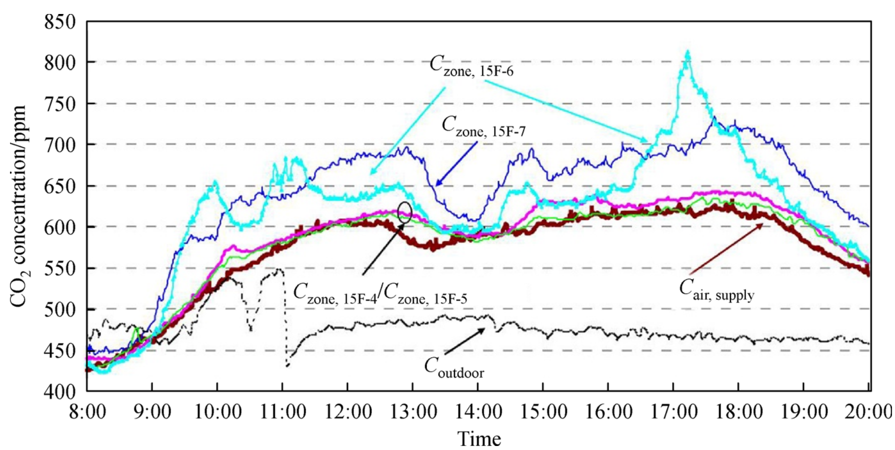


**Fig. 7** The indoor air $CO_2$ concentration of different zones at 15/F based on the DCV method

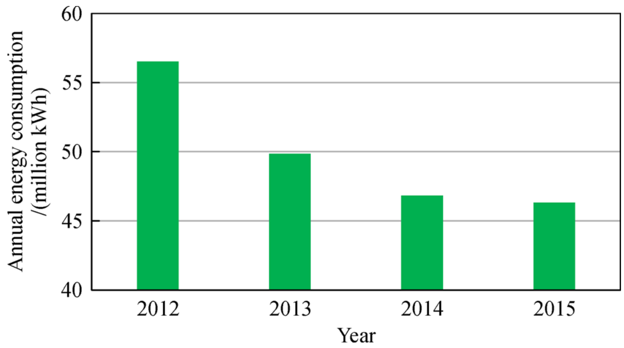


**Fig. 8** Annual energy consumption in the past four years

**Table 1** Comparison of ICC annual energy consumption

| Item | Baseline | Projected | Actual (2012) |
|---|---|---|---|
| Total energy consumption/MWh | 83,898 | 58,582 | 52,805 |
| Energy use intensity (EUI)/($kWh \cdot m^{-2} \cdot yr^{-1}$) | 261.4 | 182.5 | 164.5 |
| Energy savings | – | 30.2% | 37.1% |

the strategy developments. By obtaining the annual cost saving of 7 M HKD, it can be seen that the additional investment can be paid back in a very short time, which is 8.6 months.

The above results show that the design optimization and optimal control can improve the energy performance of the building very significantly. Actually, in 2012, 2013 and 2014, the ICC management services office was awarded the "Platinum" grade of LEED CI (Leadership in Energy and Environmental Design—Commercial Interior), the "Gold" Class of LOOP (Low-carbon Office Operation Program), and the ASHRAE Technology Award, respectively.

## 5 Conclusions

Appropriate design and control of building energy systems can significantly improve the energy efficiency of buildings. This is especially important when the urbanization is promoted in China. The high efficiency will enable the building to meet the thermal comfort of users with low energy consumption. This will alleviate the issues such as the energy shortage and poor air quality due to pollutions. Methods proposed in this paper can effectively achieve significant energy saving. The design optimization can be conducted and improve the energy efficiency of building energy systems radically. The optimal control can improve the efficiency, intelligence and smartness of building energy systems under almost all the operation conditions. All these design optimization and optimal control methods provide a solid foundation for the development of smart cities or smart grid.

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