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A systematic and probabilistic approach for optimal design and on-site adaptive balancing of building central cooling systems concerning uncertainties

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Abstract

In current design practice, chillers and pumps are often oversized due to conservative consideration of uncertainties using safety factors to avoid the risk of undersizing, which often results in significant energy waste in operation. In recent years, probabilistic optimal design methods have been proposed for the components of cooling systems, enabling risk-based decision-making rather than sizing systems with safety margins to consider uncertainties. However, approaches for probabilistic optimal design and balancing of entire cooling systems are still absent. This paper therefore presents a systematic approach of probabilistic optimal design and adaptive balancing for central cooling systems of buildings to minimize the impacts (energy waste and increased life-cycle cost) of oversizing in operation. The probabilistic optimal design considers both the uncertainties of design inputs and the flexibility of on-site adaptive balancing, while adaptive balancing enables flexible balancing to maximize energy saving according to characteristics of constructed systems. A case study is conducted to test and validate the proposed approach. Results show that significant cost reduction and energy saving were achieved for chillers and pumps, respectively, through the systematic approach of probabilistic design and adaptive balancing. Energy consumption of pumps was reduced by 41% through coordinating pump design with probabilistic chiller design.

Keywords: Optimal design; uncertainty-based design; adaptive balancing; air-conditioning system; building energy efficiency

Introduction

Buildings account for up to 40% of the end-use energy in most countries. In Hong Kong, this percentage is even up to 80% or 90% (of electricity consumption) (EMSD, 2016; Li et al., 2018). Among the building energy consumers, the heating, ventilation and air-conditioning (HVAC) systems often take up over 50% of total energy consumption (Pérez-Lombard et al., 2008). Therefore, air-conditioning system is one of the key targets for actions to save energy and reduce carbon emissions in buildings.

The conventional design of centralized air-conditioning systems usually follows standard procedures, such as that specified in ASHRAE Handbook (ASHRAE, 2009) and CIBSE Guide C (CIBSE, 2005). The conventional design of chillers is to select chillers which have the capability to meet the peak cooling load demand estimated under the pre-assumed design condition (such as weather and internal loads) and have rather high efficiency. A safety factor is introduced to consider the uncertainties in load calculation to avoid the risk of undersizing. Standbys are applied for the case of component failure and the need of maintenance in operation. However, this design method often results in oversizing of chillers, thus results in energy wastes and higher life-cycle cost (Yik et al., 1999).

The conventional design of water circulation systems is to select pumps with intersection of design flow and design pressure head on its performance curve at or close to the best efficiency point (Larralde and Ocampo, 2010). A larger value of design pressure head is often considered by multiplying the estimated pressure head of the worst circuit by a safety factor to reduce risk of undersizing similar to chiller design, and a standby is considered for each type of pump in case of failure. However, these systems are usually found oversized in practice, which leads to higher cost and particularly higher energy consumption than expected (Sowden, 2002), particularly when constant speed (CSD) water pumps are used for constant flow water systems. An important engineering practice to reduce the impacts of oversizing of CSD pumps is the use of balancing valves, which are installed to adjust the working condition of pumps to the design condition at test and commissioning (T&C) stage (ASHRAE, 2013; Mansfield, 2001). However, this balancing method adds unnecessary energy demand as the actual needed pressure head is increased when throttling the balancing valve. Though there is also a trend to use variable speed pumps to the constant flow water circulation systems, it causes unnecessary use of variable speed drive (VSD), resulting in additional energy efficiency losses and maintenance cost. Better design and balancing methods considering the uncertainties need to be developed for constant flow water circulation system to provide an alternative approach for industry to further reduce the actual impact of oversizing in operation and minimize energy consumption.

Recently, probabilistic design method or uncertainty-based design method has gained increasing attentions in building field (Wit and Augenbroe, 2002; Corrado and Mechri, 2009; Spitz et al., 2012; Wang et al., 2012; Shan et al., 2013; Shan et al., 2013; Nguyen et al., 2014; Huang et al., 2017; Kang and Wang, 2018; Tian et al., 2018). The probabilistic design methods quantify uncertainties based on a probabilistic approach, enabling risk-based decision rather than sizing systems with safety margins to consider uncertainties approximately like the conventional design methods, which may lead to oversizing (Sowden, 2002). A number of studies have been conducted on probabilistic optimal design for the components of cooling systems. Gang et al. (2016) proposed an optimal design method of chillers for district cooling systems by quantifying uncertainties in outdoor weather, building design/construction and indoor conditions. Sun et al. (2014) explores a new framework for uncertainty analysis and sensitivity analysis for HVAC system sizing. Cheng et al. (2016) proposed a robust optimal design for chilled water systems by quantifying the uncertainties of design inputs and the reliability of system component in operation.

The above probabilistic optimal design methods can mitigate the oversizing problem and maintain a high system energy efficiency in operation under the uncertain scenarios. However, these design methods are highly dependent on the accuracy of the uncertainty assumptions and do not consider balancing flexibility of actually-constructed systems. In a previous study of the authors, a probabilistic optimal design method was proposed for constant water flow pump systems by considering uncertainties and the flexibility of on-site adaptive balancing in order to further maximize energy savings (Li and Wang, 2017). But a comprehensive approach for the optimal design and adaptive balancing of entire central cooling systems is still absent. Its potential in reducing energy consumption and cost has not been investigated before, either.

In this paper, a systematic and probabilistic approach is proposed for the optimal design and on-site adaptive balancing of central cooling systems concerning uncertainties, to reduce the actual impact of oversizing and maximize energy savings. This new approach involves probabilistic optimal design of chiller plants including their water circulation systems, which facilitates on-site adaptive optimal balancing, and development of alternative balancing schemes. A case study is conducted to test and validate this systematic and probabilistic approach. The contributions of this research include a systematic approach and identification of proper design methods for different central cooling system configurations. The systematic approach facilitates effective interaction between design and balancing of entire central cooling systems and offers higher energy savings than that can be achieved by adopting probabilistic optimal design and adaptive balancing of individual components without considering the coordination between the different components of a system;

Systematic approach for optimal design and on-site adaptive balancing

Outline of the systematic and probabilistic approach

In the design stage, the proposed approach consists of two steps as shown in Fig.1, i.e., system design and development of alternative balancing schemes. The system design involves the probabilistic optimal design of chillers and probabilistic optimal design of water circulation systems. The probabilistic optimal design of chillers considers the variation of cooling load caused by uncertainties (such as uncertainties in weather and internal loads) based on a probabilistic approach, and each chiller configuration is evaluated under all possible cooling load profiles. The chiller configuration with the minimum objective value (e.g., life cycle cost in this study) is finally identified as the optimal configuration. The difference from current design practices or standard life cycle cost analysis of chillers is that the proposed method assesses the life cycle cost under possible uncertain working conditions rather than fixed and presumed conditions, while satisfying the "50 unmet hour criterion" set in the ASHRAE standard (ASHRAE, 2004). The design given by current design practices may have higher life cycle cost when the working condition deviates from the design condition since the chillers selected may be oversized or not properly sized. The detailed procedure is introduced in a previous publication of the co-author (Gang et al., 2015). In this research, design objective of chillers is average life cycle cost under design scenarios, which is obtained by dividing the sum of the life cycle cost under all design scenarios by the number of design scenarios concerned. Life cycle cost (TC) is calculated using Eq. (1). Where, *IC* is initial cost (USD), *OC* is operation cost (USD) in life cycle, *UC* is unsatisfied cooling load in life cycle (kWh), a is availability risk price (USD kWh^{-1}), which is the penalty for the unsatisfied cooling load. A higher availability risk price means a lower risk the owners/decision-makers would like to take for the situation when cooling load may be unsatisfied.

$$TC = IC + OC + a * UC \tag{1}$$

The probabilistic optimal design of water circulation system is then performed based on the design flowrates of the identified optimal chillers. The probabilistic optimal design of water circulation system considers uncertainties and the flexibility of adaptive balancing. Adaptive balancing, proposed in a previous study of the authors (Li and Wang, 2017), is a process of identifying proper pump-load (i.e., flow demand) matching and then balancing water flowrate based on the actual on-site situation to maximize pump energy saving while achieving the expected design flow. Unlike conventional balancing, which “forces” pumps to work at the design condition by throttling, adaptive balancing keeps throttling as little as possible to reduce the addition of unnecessary pressure head. Pump-load matching with fewer or smaller pumps is identified and used to meet the requirement of design flowrate under the reduced pressure head.

At first, conventional design pressure head is calculated. After that, the probability density distribution of pressure head is obtained by considering uncertainties. A “target pressure head” concerning oversizing of conventional design with high probability is then determined. Optimal pumps are finally selected, which can satisfy both the requirement of conventional design condition and the “target condition” for on-site adaptive balancing. This offers the pumps the ability and flexibility to maximize energy saving through adaptive balancing when the pumps selected are oversized by a certain degree in an actually constructed system or providing the same performance level of conventional design otherwise. The satisfaction of conventional design condition is required to avoid the risk of undersizing. Alternative balancing schemes for each chiller combination are developed in the design stage by considering different possible oversizing degrees. More details can be found in the previous publication (Li and Wang, 2017). In the T&C stage, the on-site adaptive balancing is performed by identifying the best balancing scheme among all alternative schemes based on the actual oversizing degree of the constructed system and eventually adjusting the system to the corresponding optimal balancing point. It is worth noticing that, as fouling is an important factor resulting in the increase of water loop hydraulic resistances in operation, rebalancing or choice of another alternative balancing scheme might be needed after a long period operation if the pump head is not sufficient to deliver the required water flow after periodical cleaning.

The proposed approach offers a major innovation over the current design and commissioning standard and practice. This innovation is provided on the basis of meeting the current design standard and regulations (i.e., the design of chillers satisfies the "50 unmet hour criterion" set in ASHRAE standard (ASHRAE, 2004), and the design of pumps satisfies the capabilities required at design conditions after considering a safety factor). One of the two main differences between the proposed method and conventional method for design & balancing of cooling systems or the two main advances of the proposed method is the means to handle uncertainties. In the conventional practices, a fixed design condition is considered in the design stage and the uncertainties are considered using empirical or experience-based "safety factors" and "standbys". The proposed design method considers all possible scenarios (and their probabilities) in design by quantifying uncertainties based on a probabilistic approach. It is worth noticing that though a lot of methods are available to quantify the uncertainties, the ranges or distribution types of the uncertainties involved in chiller plant design need further quantitative study prior to wide use of probabilistic optimal design in practice. The second difference/advance is that the proposed method integrates design and balancing as coordinated processes. The probabilistic optimal design considers the flexibility and possibilities of balancing of designed systems involving different possible working conditions and the optimal balancing scheme among all alternative schemes prepared in design stage is identified and implemented in the T&C stage, while the conventional balancing only implements the “fixed” balancing scheme to realize the expected design condition. With these two considerations, the design and balancing offered by the proposed method can achieve better or at least the same level of performance in operation compared with current design and balancing practices.

Design and balancing methods for different system configurations

Five typical cooling system configurations are identified and illustrated by the schematics shown in Fig.2. *Configuration A* consist of multiple chillers, cooling water system with constant-speed pumps, and constant primary/variable secondary chilled water system with multiple constant-speed primary pumps. *Configuration B* consists of multiple chillers, cooling water system with constant-speed pumps, and one-to-one (one pump serving one chiller) constant primary/variable secondary chilled water system. *Configuration C* consists of multiple chillers, cooling water system with constant-speed pumps, and variable primary-only chilled water system. *Configuration D* consists of multiple chillers, one-to-one cooling water system, and variable primary-only chilled water system. *Configuration E* consists of multiple chillers, one-to-one cooling water system, and one-to-one constant primary/variable secondary chilled water system.

Proposed design and balancing methods corresponding to the above five typical air-condition system configurations concerned are presented in Table 1. All configurations involve multiple chillers and probabilistic chiller optimal design is proposed. The primary chilled water system of *Configuration A* and the cooling water systems of *Configurations A, B, C* involve multiple constant-speed pumps connected in parallel to serve multiple chillers and they should adopt the proposed probabilistic optimal design and on-site adaptive balancing methods for water circulation systems. The other chilled water and cooling water systems involve either one-to-one pump-chiller arrangement or variable-speed pumps, the need and saving potential of the proposed methods is low. Conventional design and balancing methods are recommended for them. Thus the proposed systematic approach is recommended for *Configuration A, B* and *C*.

Design case study and test results

Description of the reference building and centralized cooling system

A building in the campus of The Hong Kong Polytechnic University is chosen as the reference building for the design case study. The design peak cooling load of the building is 7,600 kW. The existing design provided by the design consultant, based on conventional design method, is as follows. 5 identical water cooled chillers (including 1 standby) with a cooling capacity of 2,280 kW (a safety factor of 1.2 is considered) are used for supplying cooling. 5 identical constant-speed cooling water pumps (including 1 standby) are used for the condenser cooling water circulation. The design flowrate of each pump is 128.6 L s^{-1} and the design pressure head is 320 kPa (a safety factor of 1.15 is considered). The design of chillers and cooling water system of this reference building is used to test and validate the proposed approach. The design of the cooling water system is considered only since the design process of chilled water system and cooling water system are similar, so the design of cooling water system is taken as an example to demonstrate the proposed approach. The optimal chiller design using the proposed method is compared with the conventional chiller design (the design given by the consultant). The optimal pump design using the proposed method is compared with the conventional pump design by authors (namely "conventional pump design") based on the water flow rates needed by chillers of probabilistic optimal design. This conventional pump design is also compared with the design given by the consultant for the chillers of their design (namely "consultant pump design"). An architecture model is built according to the reference building using OpenStudio Sketchup plug-in (Guglielmetti et al., 2011), as shown in Fig.3, for estimating building cooling load.

Results of probabilistic optimal design for chillers

Generation of cooling load profile involving uncertainties

Three categories of uncertain design inputs, which have significant impacts on building cooling load, are considered for probabilistic optimal design of chillers. They are weather condition, internal loads and infiltration. Their probability distributions are presented in Table 2. The uncertainties of weather condition include the uncertain variation of weather condition and the uncertainty of future climate change trend (a linear increase in dry-bulb temperature over the life-cycle). In this study, the uncertain variation of weather condition (such as dry-bulb temperature, solar radiation, relative humidity, wind speed and wind direction) is quantified using the randomly-ordered actual measured weather data in Hong Kong, which is revised on the basis of the method recommended by Sun et al. (2014). In terms of the uncertainty of climate change trend over the building life cycle, the future change trend of dry-bulb temperature is considered only as the dry-bulb temperature is the climate parameter which is most significantly affected by the global warming. The change trend in the temperature is assumed to follow a uniform distribution within a range between 0 and 0.048 K $year^{-1}$. This maximum value is assumed referring to the actual dry-bulb temperature increase of +0.012 K $year^{-1}$ (from 1885 to 2017) as reported by the Hong Kong Observatory (2018), together with the consideration of urban island effect. The weather condition for each design scenario is, therefore, generated following two steps. In the first step, weather data of 20 years (assumed building life-cycle in this study) are randomly sampled from the actual historical weather data (1979-2016) in Hong Kong. In the second step, the climate/temperature change trend is sampled according to its distribution, which is added to the weather data of the sampled 20 years. The uncertainties of internal loads are quantified by multiplying an uncertainty factor by the design value of occupancy density, lighting load and equipment load, assuming that all of these are correlated to occupancy density. The uncertainty factor is assumed to follow a triangular distribution.

120 design scenarios are generated by sampling according to the probability density distribution of the concerned uncertain design inputs (including climate change trend but excluding other weather condition variables) using Latin hypercube sampling method (Stein, 1987). These 120 design scenarios are simulated over the entire building life-cycle (20 years) with a total 2,400 (20×120) years of simulations to generate the hourly cooling load profiles. In this study, building cooling load simulations are conducted using a commonly-used building simulation software, EnergyPlus (Crawley et al., 2001). Fig.4 shows the probability distribution of the hourly cooling load of all 2,400 simulated years (i.e., probabilistic test case) compared with that of the reference case using typical year weather data (conventional/consultant design). The hourly cooling load of test case varies within a range between 29 and 9,399 kW. It has a rather high probability (i.e., 33%) within the range between 341 kW and 403.5 kW. The hourly cooling load of the reference case, estimated using the conventional method, has a narrower variation range compared to the test case. It varies between 261 and 7,626 kW, and has a high probability of 61% (or 61% of time) when hourly cooling load is below 1,000 kW. Therefore, the identical chillers given by conventional design is very likely to operate at low efficiency for a rather long period. The peak cooling load of the reference case, estimated using the conventional method, occurs at an accumulative probability of 0.9993 in the test case. The total chiller design capacity of the reference case, if multiplied by a safety factor of 1.2, has a high accumulative probability of 0.9999. It means that, using the conventional design method, the probability of chiller oversize is 99.99% according to the

estimation. Therefore, it is necessary to consider uncertainties in the design of chillers to mitigate the oversizing problem.

Optimization of chiller configuration

A maximum two chiller models/capacities of the same type are considered to be reasonable for the chiller design in this study. The chillers of larger capacity are called 'large chillers' in the following sections, while the chillers with smaller capacity are called 'small chillers'. Table 3 shows the chiller options to be considered in the design. The searching range of the number of large (duty) chillers is between 2 and 6 with a searching interval of 1 based on the normal practice, while the searching range of the number of small (duty) chiller is between 0 and 1. The maximum number of small chiller is set as 1 since the small chiller is used to maintain a high operation efficiency when the load is too low to operate large chillers at high efficiency and the cooling supply capacity of two small chillers can be satisfied using one large chiller with less initial cost in most cases. The searching range of the large chiller capacity is set between 400 and 5,000 kW with a searching interval of 10 kW based on the distribution of peak cooling load. The capacity of small chiller is determined based on the capacity ratio of small chiller to large chiller as well as the capacity of large chiller. The searching range of the capacity ratio is set between 0.3 and 0.6 with a searching interval of 0.05. The chiller operation load limit is set as 0.2 (20%) of the chiller design capacity. Different availability risk prices within the range between 0.2 and 2 USD kWh^{-1} are tested. The upper limit of the availability risk price is determined to make sure the unsatisfied cooling load is within an acceptable level (for instance, 50 unmet hour criterion as set in the ASHRAE standard (ASHRAE, 2004)), while the lower limit is determined to be larger than the electricity cost for supplying 1kWh of cooling load. A total number of 18,440 chiller configurations are tested and assessed using life-cycle cost under the 2,400 years' cooling loads generated. The optimal chiller configurations with the minimum life-cycle cost corresponding to different availability risk prices are identified.

Under a fixed chiller capacity ratio of 0.3 and an availability risk price of 1.2 USD kWh^{-1}, the life-cycle costs of different chiller configurations are presented in Fig.5. It can be seen that the life-cycle costs of all configurations of different chiller numbers decrease significantly at first with the increase of the chiller capacity and then increases. This is because the increase of chiller capacity can largely reduce the unmet cooling load and thus reduce the risk cost when the chiller capacity is too small. When the chiller capacity is large enough, the increased initial and operation cost of increased chiller capacity will be higher than the reduced risk cost. Chiller configurations consisting of both large and small chillers are better than chiller configurations with identical chillers only, when the chiller capacity is large. This is due to the fact that the use of a smaller chiller significantly reduces the interval of operating chillers and thus allows the operating chillers work at higher load ratio and efficiency.

The optimal chiller configurations with the minimum life-cycle cost corresponding to different availability risk prices are shown in Fig.6A. It can be seen that all identified optimal chiller configurations, corresponding to different availability risk prices, involve both large chillers and a small duty chiller. When the availability risk price is set between 0.2 and 0.8 USD kWh^{-1}, the optimal chiller configurations involve three large duty chillers (from 1,990 kW to 2,200 kW each) and one small duty chiller (from 651 kW to 742 kW). When the availability risk price is set between 1 and 2 USD kWh^{-1}, the optimal chiller configurations involve four large duty chillers (1,700 kW and 1,770 kW) and one small duty chiller (522 kW and 595 kW). The optimal capacity of large chillers increases with the increase of availability risk price when the number of large chillers is fixed, and the total capacity of large and small duty chillers increases with the increase of availability risk price. The optimal capacity ratio of small chiller to large chillers is 0.3 except when the availability risk cost is 0.2 USD kWh^{-1}, 0.4 USD kWh^{-1} and 1 USD kWh^{-1}. This is because large difference exists between the cooling loads in the office hour and non-office hour.

The initial cost of the optimal chiller configuration has a clear increase trend with the increase of availability risk price, while its corresponding operation cost only fluctuates within a small range, as presented in Fig.6B. The unsatisfied cooling load of the optimal chiller configuration has a clear decrease trend with the increase of availability risk price. The optimal chiller configuration corresponding to the availability risk price of 0.4 USD kWh^{-1} is finally recommended and used in the following further analysis. It consists of 4 large chillers (including 1 standby) with a cooling capacity of 2,120 kW and 2 small chillers (including 1 standby) with a cooling capacity of 742 kW. The required cooling flow rate of the large chillers is 120L s^{-1} and the required cooling flow rate of the small chiller is 42 L s^{-1}. The annual average unmet hour of this chiller configuration under all the possible design scenarios is 23.3 hours only, which well meets the requirement of "50 unmet hour" set in ASHRAE standard (ASHRAE, 2004). It is worth noticing that the limit of 50 unmet hour in a typical year required in the standard is applied to the annual average unmet hour over the life-cycle in this study.

The optimal chiller design using the proposed method are compared with the conventional/consultant chiller design as presented in Table 4. The annual average initial cost of chillers selected using the probabilistic optimal design method is 0.3% lower than that of conventional design, though one more chiller is included in total (including standbys). The annual average operation cost of the probabilistic optimal chiller configuration is 1% higher than that of conventional design. This is because all chillers of conventional design are very large and no chiller can operate during a long period when the cooling load is below their operation load limit, as shown in Fig.4 and Table 4. However, the annual average operation cost would be 11% lower, as calculated if giving the assumption that chillers could operate even when cooling load is below their operation load limits for both chiller designs. This indicates that a higher energy efficiency is achieved in operation by probabilistic optimal design compared to conventional design besides avoiding the frequent chiller switching-off at low load. The unmet cooling load and unmet hour (1,558 kWh, 9 h) of chillers of the probabilistic optimal design is slightly larger than that of conventional design (0 kWh, 0 h) in typical meteorological year (TMY), because its total chiller capacity is smaller. Both of these two chiller configurations well meet the requirement of "50 unmet hour" in TMY, set in ASHRAE standard. However, the conventional design method, adopting a safety factor, overestimates the capacity needed in this case. The annual average life-cycle cost of the chillers is decreased by 39.8% using the proposed method compared to the conventional design in the years concerning uncertainties. It can be seen that the design given by probabilistic optimal design method can achieve a much lower life-cycle cost and higher operation efficiency compared to the design given by conventional design method.

Results of cooling water system probabilistic design

Generation of pressure head distribution involving uncertainties

Corresponding to the required cooling flow rates of 120 L s^{-1} and 42 L s^{-1} for the selected large and small chillers, the calculated pressure loss is 220 kPa. According to conventional design method, the design pressure head is selected to be 242 kPa after introducing a safety factor of 1.1. The main uncertainty variables associated to the pressure head of a cooling water loop are friction coefficients of pipes, pressure loss factors of pipe fittings, pressure for nozzle spraying in cooling tower, pressure loss in system components, elevated height from water level to spraying nozzle in cooling tower as well as the pipe lengths and diameters. The quantification of uncertainties in these variables is elaborated in our previous study (Li and Wang, 2017). 100,000 uncertain design scenarios are generated by sampling from these uncertain design inputs using Monte Carlo simulation method (Mooney, 1997). The probability distribution of the pressure head is obtained as shown in Fig.7. The pressure head varies in a range between 168 and 228 kPa. The target pressure head is chosen as 194 kPa corresponding to a probability of 0.406 (40.6%). The associated target oversizing degree is then 20% for the further selection of suitable pumps to facilitate adaptive balancing.

Selection of optimal pumps

At first, proper pumps are selected from the available pump data base from a manufacturer (Grundfos's Corporate, 2019) using the conventional pump design method based on the flowrate requirements of chillers selected. The performance curve of these pumps are shown in Fig.8. The energy demand of these selected pumps are 41% less than that of the pumps given by the consultant at the design load condition when all duty pumps are in operation in both cases. This indicates that the proposed system approach, coordinating pump design with probabilistic chiller design, can provide higher energy saving for pump systems. It also shows the necessity and benefit of probabilistic chiller design method from the viewpoint of pump energy consumption. Suitable pumps for adaptive balancing are then searched. Three models can meet the selection requirements for the large pump, and two models can meet the selection requirements for the small pump. 4 balancing intervals are presumed based on the determined oversizing degree, i.e. 0%-10%, 10%-15%, 15%-20%, and over 20%. Mean energy consumption at the presumed balancing points for each pump option is calculated and compared. At last, the optimal models with the minimum mean energy consumption are identified for the large pump and the small pump, respectively, as shown in Fig.8. The set of pump models finally selected has the characteristics as follows. One small pump and one large pump can provide the design flow rate of one small chiller and one large chiller, respectively, as normal at the conventional design pressure head (i.e., 242 kPa). If the pump system is oversized for 20% (i.e., at pressure head of 194 kPa), one small pump can meet the design flow rate needed for one large chiller, and one large pump can satisfy the design flow rate needed for one large and one small chiller. Three large CSD pumps, three small pumps (including one CSD pumps and two VSD pumps (one as standby)) are eventually selected for the cooling water system.

Alternative balancing schemes

0%-10%, 10%-15%, 15%-20% and over 20% oversizing are found to be the best balancing intervals which can be satisfied by the pumps selected based on the available pumps. For different combinations of operating chillers, the alternative balancing schemes for different pressure head intervals are identified to satisfy the flowrate requirements and achieve maximized energy saving as shown in Table 5. It is also found that there are two or more alternative schemes that can be used for the same operating chiller combinations as listed in the table. These workable pump schemes with slightly lower operation efficiency than the best pump scheme under certain oversized condition can be used in case of pump failure. The energy savings of these alternative balancing schemes within different balancing intervals are also analyzed. The maximum pump energy savings of the pump balancing schemes, compared with the conventional design and balancing method, are presented in Table 5. It can be seen that significant energy savings can be achieved by the alternative balancing schemes (or pump schemes) obtained using the proposed design and balancing method except the case when conventional balancing needs to be conducted. If the oversizing is 20% or more, which has an estimated probability of 40.6%, the proposed method can achieve an energy saving of about 12.7%-22.8%. If the oversizing is over 15% and below 20%, which has an estimated probability of 45%, the proposed method can achieve an energy saving of about 9.0%-26.6%. If the oversizing is over 10% and below 15%, which has an estimated probability of 14%, the proposed method can achieve an energy saving of about 0.6%-18.5%.

Conclusions

A systematic and coordinated design and balancing approach is proposed for building central cooling systems concerning uncertainties, in order to reduce the actual impact of oversizing and maximize energy savings. This approach involves probabilistic optimal design of chillers and water circulation systems, and on-site adaptive balancing of water circulation systems. A case study is conducted to test and validate the proposed approach. Based on the results of case study, conclusions can be made as follows.

The experience of this work and the test results show that the probabilistic design method of chillers is applicable and effective for all configurations of central cooling systems, while the systematic approach coordinating the probabilistic optimal design and on-site adaptive balancing methods is effective and applicable for the configurations involving primary chilled water system or cooling water systems with multiple constant-speed pumps connected in parallel to serve multiple chillers.

The proposed systematic approach adopting probabilistic optimal design and on-site adaptive balancing methods can provide chiller designs with much lower life-cycle cost and higher energy efficiency in operation compared to conventional design method. It can also maximize the energy saving even when pumps are oversized while avoiding the risk of pump undersizing. In addition, it can provide higher energy saving of water circulation systems by coordinating probabilistic design of chillers and pumps, compared without coordinating the chiller and pump designs. The life-cycle cost of optimal chiller system given by probabilistic design in the design case study was about 40% lower than that given by conventional design, and its operation cost was also about 11% lower. The energy consumption of pumps was reduced by 41% through coordinating pump design with probabilistic chiller design. It was further reduced by 9.0%-26.6% using probabilistic pump design and on-site adaptive balancing methods when oversizing degree is over 15%. Though the proposed method shows some advantages over the conventional design method, the application of this method in engineering practice needs further work.

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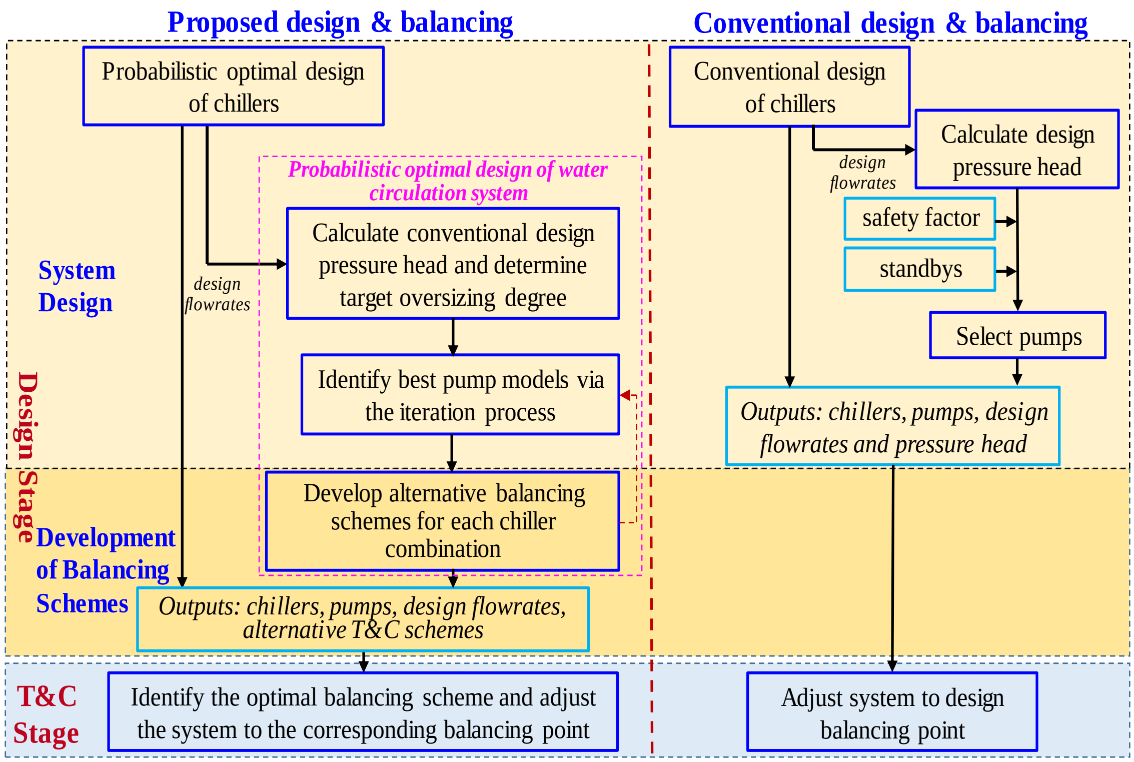


Fig. 1. Procedures of proposed and conventional "design & balancing" approaches

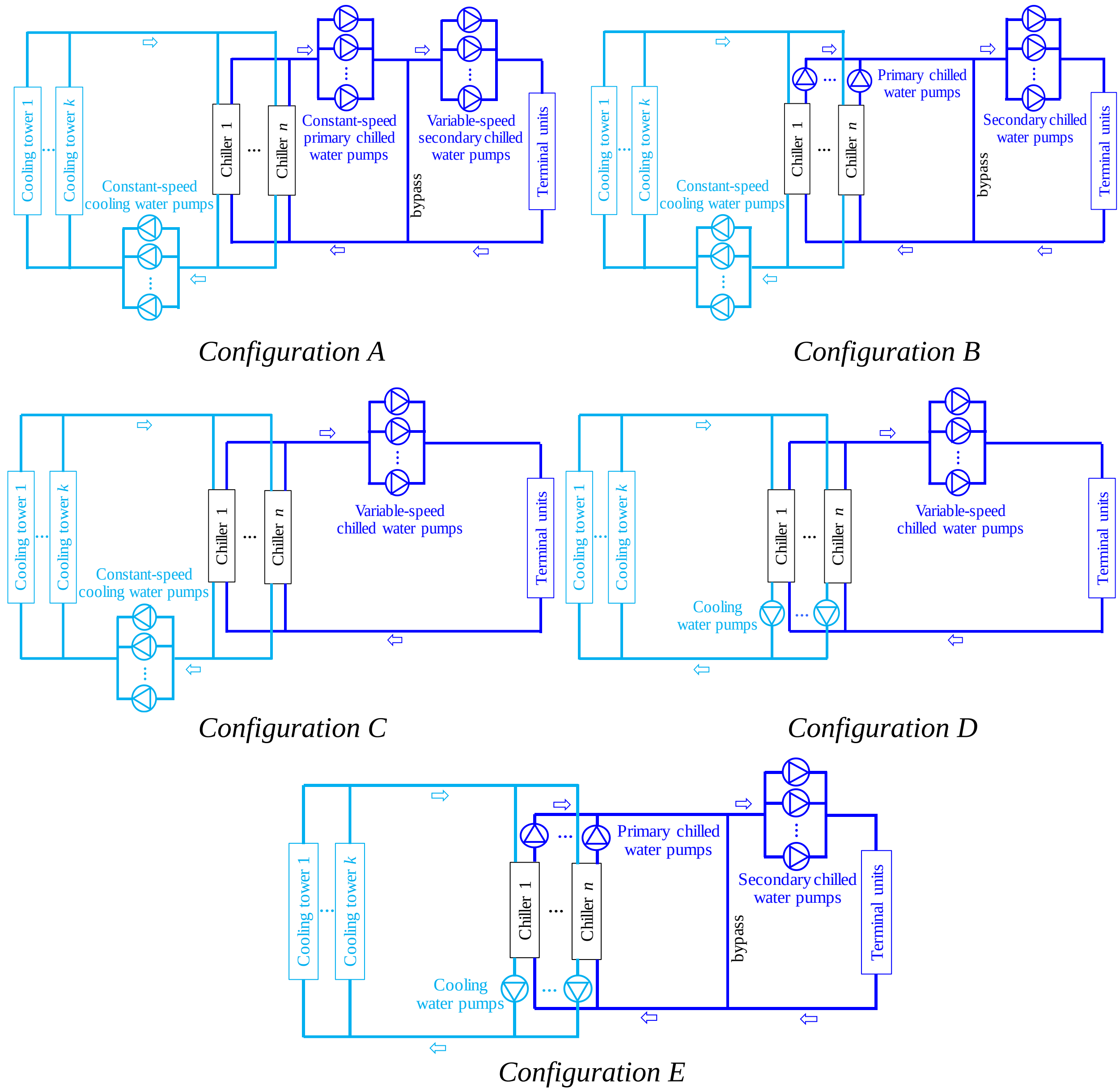


Fig. 2. Typical configurations of central cooling systems concerned

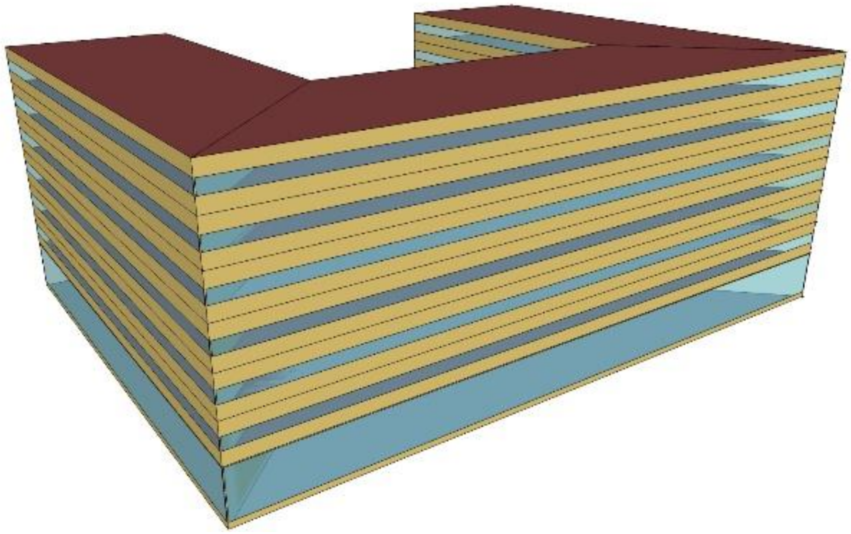


Fig. 3. Architecture model of the reference building for building cooling load estimation

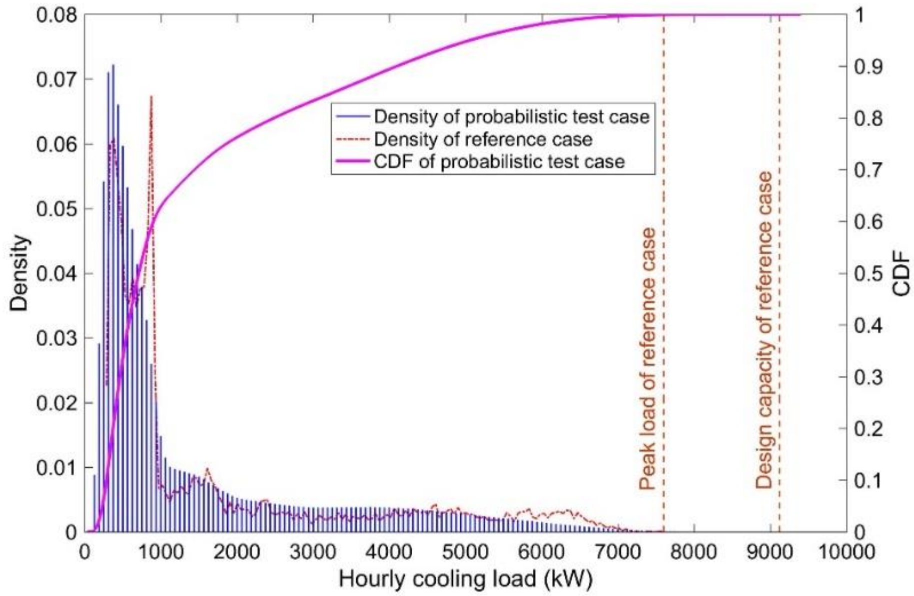


Fig. 4. Probability density distribution of hourly cooling load concerning uncertainties and comparison with estimation using conventional method

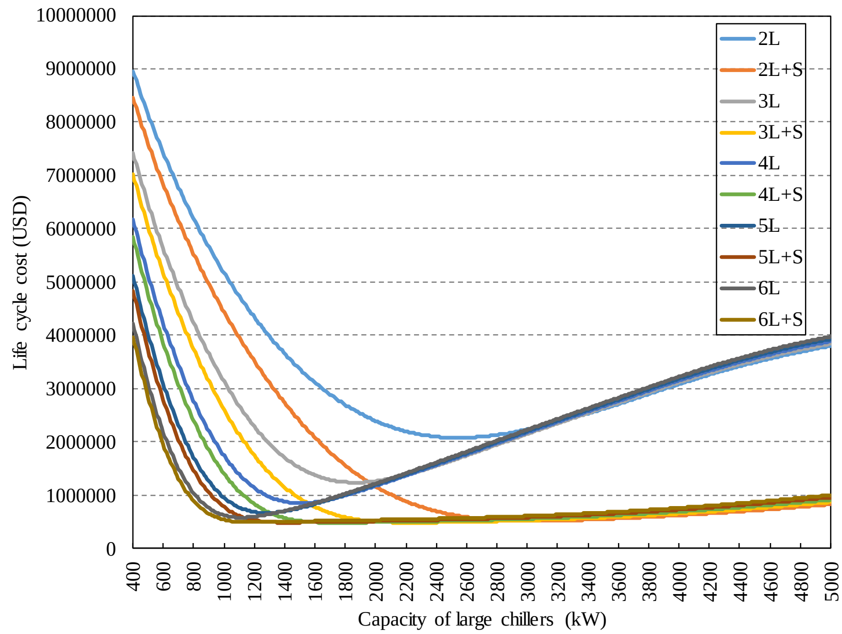
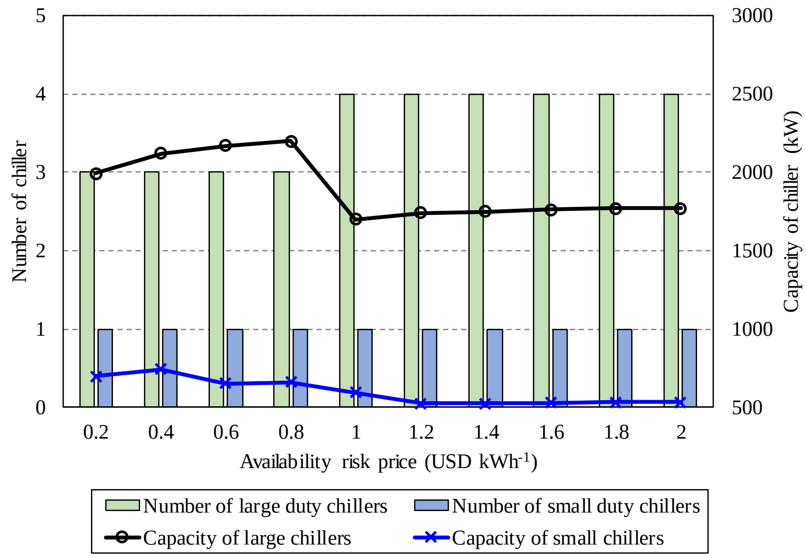
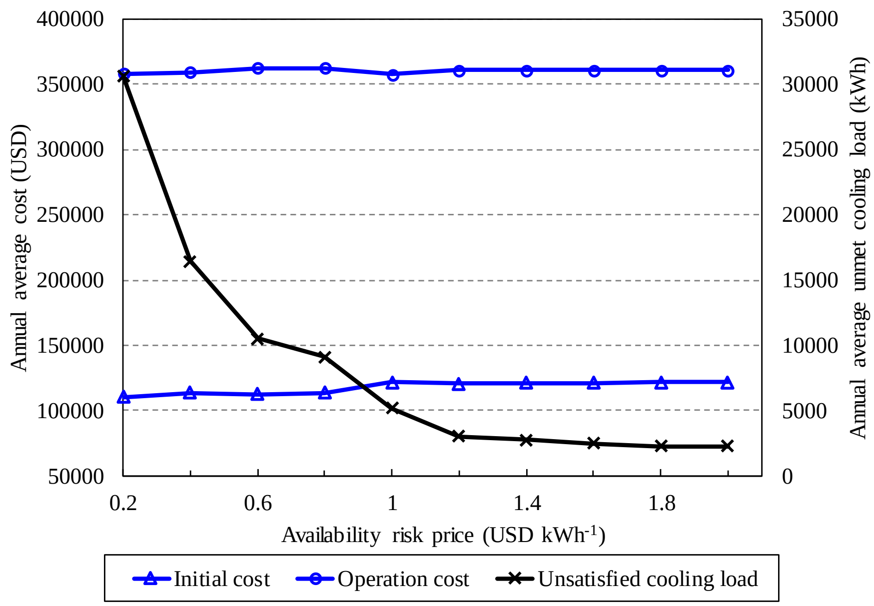


Fig. 5. Life-cycle costs of different chiller configurations vs chiller capacity *(capacity ratio= 0.3, availability risk price =1.2 USD kWh^{-1})*



(A): Optimal chiller configuration (number and capacity)



(B): Annual average cost and unsatisfied cooling load of optimal chiller configuration

Fig. 6. Optimal chiller configurations and their performance at different availability risk prices

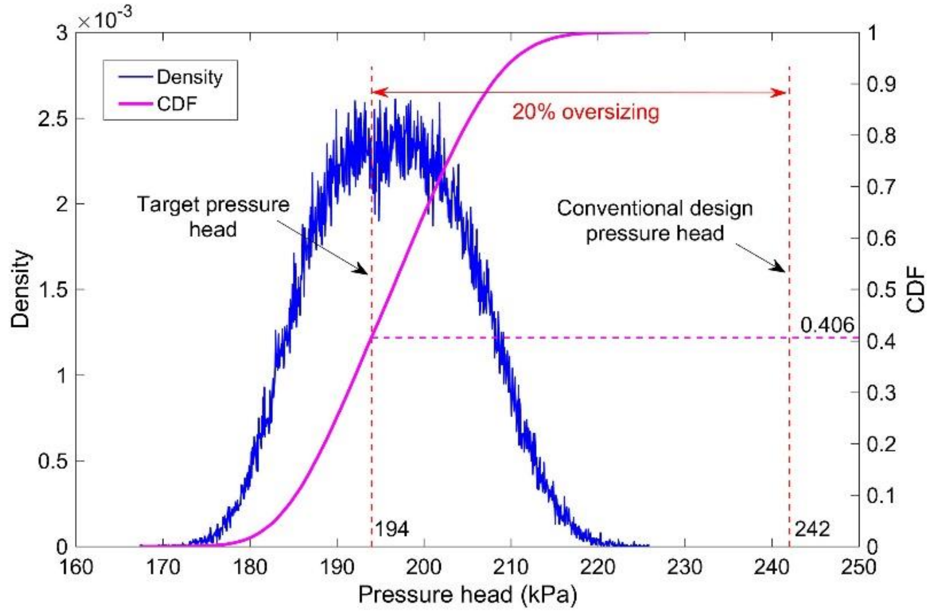


Fig. 7. Probability distribution of actual pressure head and projected oversizing degree

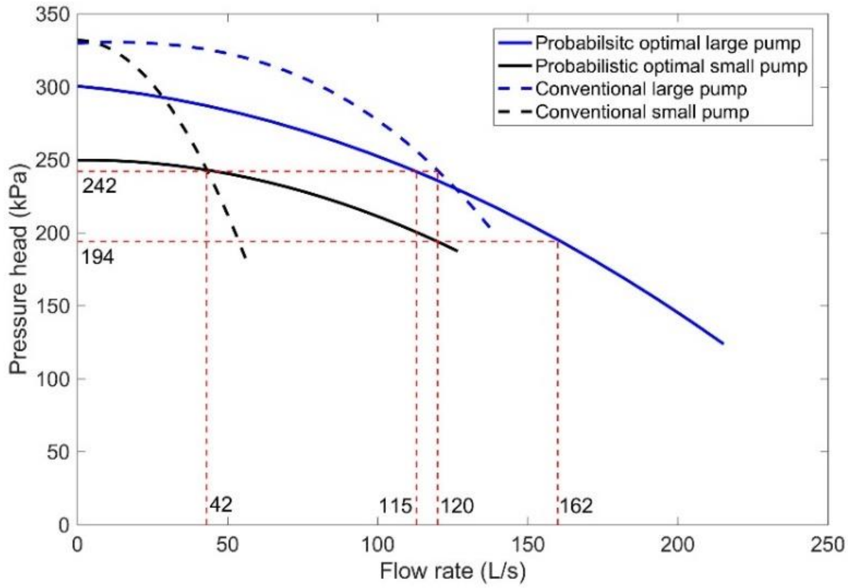


Fig. 8. Performance curve of the selected pumps using the proposed and conventional methods

Table 1. Design and balancing methods for different cooling system configurations

Configuration No.	**Design & balancing method**		
	Chiller	*Chilled water system*	*Cooling water system*
A	Probabilistic optimal design	Primary: probabilistic optimal design and on-site adaptive balancing Secondary: conventional design and balancing	Probabilistic optimal design and on-site adaptive balancing
B	Probabilistic optimal design	Conventional design and balancing	Probabilistic optimal design and on-site adaptive balancing
C	Probabilistic optimal design	Conventional design and balancing	Probabilistic optimal design and on-site adaptive balancing
D	Probabilistic optimal design	Conventional design and balancing	Conventional design and balancing
E	Probabilistic optimal design	Conventional design and balancing	Conventional design and balancing

Table 2. Uncertain design inputs considered for probabilistic optimal design of chillers

Category	**Uncertain design inputs**	**Unit**	**Distribution**
Weather condition	Dry bulb temperature	°C	Actual measured weather (1979-2016)
	Relative humidity	%	
	Solar radiation	Wh m^{-2}	
	Wind speed	m s^{-1}	
	Wind direction	-	
	Climate change trend	K $year^{-1}$	U(0,0.048)
Internal loads	Occupancy density	-	Factor: Tri(0.3,1.2,0.9)
	Lighting load	-	
	Equipment load	-	
Infiltration	Infiltration air mass flow rate	$hour^{-1}$	U(0.5,1.5)

Note: U (p, q) is a uniform distribution, where p refers to the minimum value and q refers to the maximum value. Tri (m, s, n) is a triangular distribution, where m, n, s refers to the minimum value, the maximum value, and the peak value, respectively.

Table 3. Chiller options considered in the design

Design variables	Searching range	Searching interval	Unit
Capacity of large chillers[a]	[400, 5000]	10	kW
Number of large duty chillers[a]	[2, 6]	1	-
Capacity of small chillers[b]	Capacity ratio * capacity of large chillers	-	kW
Number of small duty chillers[a]	[0, 1]	1	-
Capacity ratio of small chillers to large chillers[a]	[0.3, 0.6]	0.05	-

Note: a – independent variables, b – dependent variable determined by other independent variables.

Table 4. Comparison of optimal chiller configuration and its performance of probabilistic optimal design and that of conventional design

Design method	Optimal chiller configuration (including standbys)	Performance of optimal chiller configuration						
		Annual average initial cost (USD)	Annual average operation cost (USD)	Cooling load is below operation load limit		Annual average life-cycle cost (USD)	Unmet cooling load in TMY (kWh)	Unmet hour in TMY (hour)
				Annual average cooling load (kWh)	Annual average hour (hour)			
Probabilistic optimal design	4 nos. of 2,120 kW + 2 nos. of 742 kW	113,628	359,263 *359,726*	8,546	67.8	479,467	1,558	9
Conventional design	5 nos. of 2,280 kW	114,012	355,812 *404,277*	816,025	2554.1	796,234	0	0

Note: the operation cost values in italic are calculated by assuming that chillers can operate when cooling load is below chiller operation load limit.

Table 5. Adaptive balancing schemes for different oversizing degrees and their maximum energy saving (%) compared with conventional design and balancing

Operating chiller combinations	Oversizing degree (OD)							
	0<=OD<10%		10%<=OD<15%		15%<=OD<20%		OD>=20%	
1S	1S	-6.7	1S (VSD)	4.3	1S (VSD)	9.0	1S (VSD)	13.0
1L	1L	1.1	1L	0.6	1S/1L	24.9	1S	22.8
1L+1S	1L+1S	-0.9	2S	6.3	1L/2S	26.6	1L	20.8
2L	2L	1.1	1L+1S/2L	18.5	2S/1L+1S	24.9	2S/1L+1S	22.8
2L+1S	2L+1S	-0.1	2L/1L+2S	15.7	1L+1S/2L	25.9	1L+1S/2L	21.7
3L	3L	1.1	2L+1S	12.5	1L+2S/2L+1S	16.7	1L+2S/2L+1S	12.7
3L+S	3L+S	0.3	3L/2L+2S	11.2	2L+1S/3L	18.2	1L+2S/2L+1S/3L	22.0