Optimizing the topologies of HVAC chilled water systems in supertall buildings

The vertical topologies of HVAC water systems in supertall buildings are one major concern, which yet has been determined in experience-based manners. This papers, therefore, proposes a computational optimization procedure to search optimal design of system topologies, as well as component sizing and control settings. To reduce the computational efforts, the vertical topologies are simplified by considering only major components(e.g. AHUs, heat exchangers and chillers).Since both electricity consumption and capital cost are primary concerns for system design, the optimization problem has been solved using a two-objective solver, Non-dominated Sorting Genetic Algorithm II(NSGA-II). This optimization problem is then validated using a supertall building in Shanghai, and it is concluded that the generated solutions are superior in terms of both electricity consumption and capital cost. Finally, parametric analyses are conducted to provide insight into the uncontrollable variables (i.e., building location, building characteristics) with the hope that system design can be facilitated.

1. Introduction

The Council on Tall Buildings and Urban Habitat (CTBUH) defines a “supertall building” as a building over 300 meters in height. In past few decades, Asia’s rapid process of urbanization has driven a growing development of supertall buildings, especially in China and the Middle East. According to data collected at the end of 2013, of the current 20 tallest completed buildings in the world, 10 are in China (Safarik and Wood 2014), and the number of supertall buildings in Asia is projected to increase in the next decades. This trend demands a rethinking of Heating, Ventilation and Air Conditioning (HVAC)water system design that addresses the complex nature of these types of buildings.

The height of a supertall building makes the hydrostatic pressure of its HVAC water system a major design problem because the hydrostatic pressure at the bottom of a vertical water system is proportional to the building height. The hydrostatic pressure affects not only the piping and its associated valves but also the equipment connected by the pipes. The costs of these components increase as the pressure they bear increases. One common approach with which engineers solve this problem is to add heat exchangers in the water loop and to divide the whole building into several vertical zones. Figure 1 is a typical example of such a water system. Adding heating exchangers significantly reduces the working pressure of components, but their side effect is an increased chilled water temperature. After each heat exchanger, the chilled water temperature will increase approximately 1-3 °C. In the secondary side of a heat exchanger, cooling coils and other terminal equipment are sized larger than in the primary system. Higher chilled-water temperature consequently increases the purchase cost of the equipment and decreases the thermal performance of the whole system. In any supertall building, the maximum number of sequential heat exchangers that can be used is two. The topology limitation dictates that the system configuration be a priority in HVAC water system design. In this sense, an optimal design scheme is a trade-off between capital cost and ongoing energy consumption. These two considerations therefore form the objectives of our optimization problem.

HVAC water system topology is only the first step in the design process. The subsequent sizing and the supervisory control of systems are also important to obtain an optimal solution since supervisory control of HVAC systems have significant impacts on the energy or cost efficiency of buildings (Wang, Ma 2008). In other words, HVAC water-system design is a multi-level design problem. The conventional design of such a system is a sequential experience-based method that can fail to work out an optimal solution mainly because of the following two aspects. On one hand, the system design is conducted in a sequential manner, that is, choosing a system configuration first, then sizing the components and finally developing a control strategy. At each step, engineers only consider the advantages and disadvantages of their choices at that step without examining the overall energy impact. On the other hand, because of the relatively short history of supertall building HVAC water-system design, the accumulated experience in the designer community is insufficient to assist in finding an energy-efficient design. This calls for a new alternative design approach that addresses these challenges.

Figure 1. Schematic of an HVAC water system in a supertall building

To date, optimization methods have been widely used to aid HVAC system design. J. Wright has proposed a method for automatic design optimization for HVAC secondary systems (Wright 1986). He and his colleagues formulated a single-objective optimization problem for a single air-conditioned zone, a problem that seeks solutions to the simultaneous optimization of building fabric construction, the size of the HVAC system, and the plant supervisory control strategy (Wright and Farmani 2001). They also conducted a multi-objective optimization of the HVAC secondary system design and control by sizing coils and fans and setting control variables (Wright, Loosemore, and Farmani 2002). Asiedu et al. have also applied automatic design optimization methods to minimize life-cycle cost by sizing air ducts (Asiedu, Besant and Gu 2000). The presented approach has the capability to incorporate standard (discrete) duct sizes, variable time-of-day operating conditions and variable time-of-day utility rates. Ooka, R. et al. proposed a design optimization process for the HVAC system in an apartment to select the type of source plants automatically (Ooka and Komamura 2007; Seo, Ooka, and Kim et al. 2014). Integrating with the design optimization of the building envelope and fabric, Michael Wetter et al. have examined several optimization algorithms to optimize HVAC system design (Wetter 2000; Wetter 2005).

All of the previous research focuses mainly on optimizing the sizing and control parameters. No research has been conducted to investigate HVAC water system topology, let alone to compare the optimum results of water system design under different topologies.

Additionally, research on optimal designs of HVAC systems in high-rise buildings is greatly limited. Langner and Henze et al. have investigated the design parameters of a commercial high-rise office building (Langner, Henze, and Corbin, et al. 2012). This work can be viewed as only the first step of optimal design of HVAC systems in high-rise buildings.

With foregoing gaps in mind, this paper, therefore, proposes a computational method to optimize design of HVAC water systems in supertall buildings. After reviewing the literature, this study investigates the impact of HVAC water system topology on the performance of a system design through answering these questions:

1. Will the numbers of vertical zones and plant stations affect the system cost and energy consumption of an HVAC water system significantly? If so, what are the key factors in these relationships?
2. For each combination of vertical zones and plant stations, what is the optimal HVAC water system configuration?
3. Is the design pressure level an important factor in HVAC water system design?

Because a computational method optimizes the HVAC water system configuration, system size, and the system supervisory control strategy simultaneously, the deficiencies of the conventional design approach can be addressed well.

This study is organized as follows: first, drawing on the literature, we propose a procedure for optimal design; then, HVAC water system configuration models are established in MATLAB, including system topology encodings, component models, and control strategies. This is followed by the formulation of the multi-objective design optimization problem for water systems in supertall buildings. Finally, a case study of a supertall building in Shanghai is conducted to validate the proposed procedure, and a parametric analysis is used to provide insight into the influence of uncontrollable variables (i.e., building location, building characteristics) on optimal design solutions.

2. Water System Optimization Procedure

Figure 2 shows the proposed framework of the design optimization, which contains four modules: Input data, Pre-processing, Optimal design and Post-processing. As the first module, buildingdesign information, such as weather files, building general information, internal loads and schedules, etc. are inputed into EnergyPlus to simulated the building load. Then, the dereived load file along with system information and operation schedule flow into the Pre-processing module.

The input information then flows into the Pre-processing module for two purposes: to check the accuracy of these data and to generate an input file with suffix ".mat", readable by MATLAB.

The Optimal design module then reads the input file, and begins to form and solve the optimization problems according to the input optimization requirements. After reading the design input files, this module begins to formulate a design-optimization problem, which includes initializing design variables, calculating objectives and constraints, searching for an optimal solution with optimization algorithms, and generating output files. In particular, evaluations of objective functions and constraints involve system configuration modeling, including topology encoding,

Figure 2. Framework of optimal design method

sizing equipment and setting controls. The system configuration model has a hierarchical structure whose upper level is a topology-encoding problem and whose lower level is some sizing and control-setting problems. The optimization algorithm, by comparing calculated objectives and constraints, determines when to stop searching for the best solution.

The computational design optimization is clearly of value to obtain a high-performance solution; however, its application is greatly limited by the daunting huge solution space. To solve this problem, many researchers (e.g., Brownlee and Wright, 2015) have dedicated their efforts to designing effective optimization algorithms that can be used in this scenario. Through their exploratory research, the Genetic Algorithm (GA) has turned out to be one of the most suitable methods because of its strength in searching a large space. For example, Ibrahim and Ghaddar et al. have successfully applied GA to search out the optimal locations and thicknesses of insulation layers for minimizing building energy consumption (Ibrahim Ghaddar and Ghali 2012). Therefore, in this paper, the authors have used the Genetic Algorithm to solve the optimization problem.

For a two-objective optimization problem, Non-dominated Sorting Genetic Algorithm II (NSGA-II), an efficient genetic algorithm (Deb, Pratap, and Agarwal, et al., 2002), is used to search the solution trade-offs between objectives, also called the Pareto Front. Sections 3 and 4 supply additional details about the system configuration models and the formulation of design optimization problems.

The last module is Post-processing, which is used to output and visualize the optimization results.

3. Modeling an HVAC water system

The modeling procedure of an HVAC water system in a supertall building can be divided into three steps. The first step is to encoding the system configuration, which refers to the manner in which each water-side component (e.g., chiller, chilled-water pump, plate heat exchanger (PHX), and air handling unit (AHU)) is connected. This is followed by the modeling of each component. Finally, a supervisory control strategy, which mainly refers to the operation mode and set point, is simulated. The details of each step are introduced below.

3.1. Topology Encoding

Encoding all possible topologies in a computer-readable manner is the first challenge in this optimization problem. The simplification of the system models is necessary to make this optimization problem easy to solve with reduced computational time. In this pilot study, we employed a simplified method to encode HVAC water system topology, based on the following assumptions:

1. There are two control variables related to plant stations, the number of stations and the location of each station. Again, to simplify this optimization problem, the upper limit of the number of stations is set to be 2, and each station is assumed to be located at the bottom of corresponding vertical zone.

2. Noting that the maximum number of PHXs is two because otherwise, the chilled water temperature becomes too high to use (Figure 4(left)) (Ross 2004), we constrain the number of PHXs dedicated to a plant station to be two or less to reduce the optimization search space.

3. Generally, the working pressures of different vertical zones in a building are usually different. For example, one zone operates at 2.8 Mpa, while another zone operates at a lower pressure such as 1.0 Mpa. Because the initial cost increases rapidly (approximately in an exponential manner) as the working pressure increases, the optimal solution is to divide the building evenly into several vertical zones. Therefore, in this study, the working pressure of all of the zones are assumed to be equal and proximate to the design pressure, which is a unknown variable in the design process. This means that the heights of all vertical zones all equals in our model.

4. The layout of chilled water systems should be made as simple as possible, but no simpler. A great deal of variables will be required to detail the graphical layout of a simple system. For a system with n nodes (here, nodes refer to all components in a water system except pipes, such as pumps, splitters, mixers, etc.), a $n \times n$ adjacency matrix is needed to represent the links in this system. Consequently, the search space will increase exponentially. This situation is also confirmed in this paper, where computational overload is still the primary concern for the optimization of a simple single-zone system (Wright, Zhang, Angelov, et al. 2008).

   Luckily, the energy consumption of water systems is influenced mostly by AHUs and chillers (Eisenhower, O'Neill, Fonoberov, et al. 2012), which means a proper simplification of layout of water systems will not degrade system simulation significantly. In this study, each floor is assumed to have a global AHU to deal with cooling and heating load in this area, and primary pumps and secondary pumps are placed in the outlet of supply side and the inlet of demand side, respectively.

The first two assumptions are related to the selections of PHX and plant station. Under these two assumptions, the number of plant stations and the number of PHXs can be set firstly. Then, given a feasible selection of system components, all possible topologies can be defined by the permutation of these components. For each permutation, chilled water pumps and AHUs will be automatically set to ensure that chilled water is effectively circulated.

For example, if the number of plant stations is 1 and the number of PHX is 2, there is only one possible permutation since plant station is assumed to be located at the bottom, as shown in Figure 3(left). After adding necessary AHUs and pumps, only one feasible water-side system exists.

Finally, we need to encode the above topologies construction process in data structures. In optimization field, fixed-length vectors are a well-established encoding method. Hence, we implemented a fixed-length vector for this topology encoding. As shown in Figure 4, there are four variables, the 1st and 3rd ones represent the number of plant stations in subsystem 1 and subsystem 2, respectively, and both these two variables can take 0 or 1. Note that a value of 0 will make the following variable (the number of PHXs) not applicable. The 2nd and 4th ones represent the number of PHXs in subsystem 1 and subsystem 2, respectively, and both these two variables can take 0,1 or 2.

Figure 3. (left) A permutation for $n_{station} = 1$ and $n_{PHX} = 2$; (right)Topological connection of this permutation

Figure 4. example encoding vector

3.2. Component Models

In this research, each component contains three parts: an energy model, a pressure model and a cost model. The energy model calculates heat and mass transfer. Some commonly accepted physical models are used here, such as the electric chiller model and the two-speed cooling tower model from Energy Plus (DOE 2010), the variable speed pump (Ma 2008), and the heat exchanger based on the epsilon-NTU method (Ma, Wang. 2011).

The pressure model is expressed as:

$$\Delta p = km^2 \tag{1}$$

where Δp is the pressure loss, k is the coefficient and m is the mass flow rate.

The cost model is described as a polynomial equation as shown in Equation (2).

$$C = \sum_{i=0}^{n} a_i x^i \tag{2}$$

where C is the capital cost ($), the x^i are the independent variables with strong relationships to capital cost, and the components of the vector a_i are the coefficients. The coefficient data are retrieved from RSMeans Mechanical Cost Data Book (Department 2008), as listed in Table 1.

Table 1. Capital cost models for some components

3.3. Control Strategy

Generally, for a complex HVAC system, a supervisory control strategy is used to ensure that the system operates at an efficient point. Supervisory control can globally and dynamically reset control parameters such as temperatures and pressures. In this pilot study, we adopted a virtual "supervisory controller" and idealized the control process: control parameters and variables were all available and controllable. In an optimization, supervisory controllers help determine the optimum settings of controllable components by gathering building loads and environmental parameters.

The Q-based chiller sequencing control strategy was used to optimize operation of the chillers and combined cooling towers (Liao, Huang and Sun, et al., 2014). Specific frequency control and sequencing control for secondary pumps was also adopted (Ma 2008). For plate heat exchangers and other constant speed pumps, an on-and-off strategy was used to manage their sequences (Ma 2008).

4. Design Optimization of the HVAC Water System

4.1. Objective Function

The two common objectives of system design are capital cost and operation cost; in some cases, life-cycle cost is selected as the optimization objective to carry out a more comprehensive analysis. In this study, the annual electricity consumption J_1 and capital cost J_2 were minimized. J_1 can be obtained by Equation (3), summing up all of the individual electricity consumptions:

$$J_1 = \sum_{i} \sum_{comp} P_{comp,i} \tag{3}$$

where $P_{comp,i}$ refers to the power consumption of the component, the subscript i refers to the number of hours in a year ($1 \le i \le 8760$), and comp refers to different components in the HVAC system.

J_2 is the sum of capital cost for all of the components except pipes:

$$J_2 = \sum_{comp} C_{comp} \tag{4}$$

where C_{comp} refers to the capital cost and the subscript comp refers to the different components in the HVAC system. In future research, a comprehensive life-cycle cost optimization will be studied.

4.2. Design Variables

The design variables in this study were divided into three categories: topology variables, component variables and control-strategy variables, as listed in Table 2. Component variables firstly address the sizing of plants. Based on the chiller capacities, the simulation system then sizes all of the other components such as cooling towers, plate heat exchangers, and pumps. AHUs are sized corresponding to the building loads in each zone. To simplify the sizing process, chillers are divided into three subtypes according to their capacities: small chillers with capacities ranging from 100 tons to 500 tons, middle chillers with capacities ranging from 600 tons to 1000 tons, and large chillers with capacities ranging from 1100 tons to 2000 tons. These three subtypes have their own unique performance curves, the default values of which are shown in Figure 5. Six variables (three for capacity and three for the number of each sub-type of chiller) represent the size and number of chillers in one plant station; that is, there are 12 variables to describe the sizing of source plants in two possible plant stations.

Figure 5. Three sizes of chillers with different COP~PLR curves

Three variables involving virtual supervisory control were also selected as design variables: outgoing chilled water temperature, incoming cool water temperature and AHU supply air temperature.

For the water-system topology, we add to the previous four-dimensional row vector an element that can represent the design pressure given by designers. This element directly influences the minimum number of vertical zones and guarantees that all zones work under reasonable pressure. As an engineering practice, the design pressure for an HVAC water system is a discrete variable whose values are shown in Table 3. An integer variable (Pressure Level) measures the discrete design pressure value during optimization.

Table 2. Design variables in the HVAC water system design optimization

Table 3. Design pressure level and reference value

4.3. Constraints

The optimization problem for HVAC water-system configuration design has many constraints, as follows.

C1. To evaluate the supply air (SA), we use the term Dissatisfied Hours (DH), which calculates the number of hours when the supply air temperature deviates too much from the SAT set point. This constraint is derived from the need to maintain a comfortable environment. The equation is:

$$DH_{sat} = \sum_{i} I(|T_{sa,i} - T_{sa,sp}| > \varepsilon_{sa}) \tag{5}$$

where T and ε refer to temperature and tolerance, respectively, and the subscripts i and sp refer to the ith hour and set point value, respectively. Function I is expressed as:

$$I(x) = \begin{cases} 1, x \ \ is \ \ true \\ 0, x \ is \ false \end{cases} \tag{6}$$

C2. Similarly, we also use DH to calculate the number of hours in which the working pressure (WP) in each zone deviates too much from the design pressure. This constraint is adopted to ensure that the system operates safely:

$$DH_{wp} = \sum_{i} I(|WP_i - WP_o| > \varepsilon_{wp}) \tag{7}$$

where WP and ε refer to working pressure (Pa) and tolerance, respectively, and the subscripts i and 0 refer to the ith hour and design value, respectively. Function I is the same as Equation (6).

C3. The minimum number of vertical zones and water system design pressure share the correlation shown in Equation (8):

$$NV_{\min} = \frac{H_{building}}{WP_0 - H_{pump}} \tag{8}$$

where NV, H, and WP refer to the number of vertical zones, head or height (m), and working pressure (Pa, respectively, and the subscripts min and 0 refer to minimum value and design condition.

C4. The size of plant equipment needed meets the design load in the building. Considering operational safety, a multiplier termed a safety coefficient is used to determine the upper bound for sizing.

$$L_{des} < Cap_{chi} < \alpha \bullet L_{des} \tag{9}$$

4.4. Selection of an optimization algorithm

The selection of an optimization algorithm depends on the characteristics of optimization problems(in terms of nature of the problem variables, the constraints, and the objective function).

There are 20 design variables involved with the optimization. The three set points are continuous variables and the rest variables are represented by integers. Therefore, this problem is mixed-integer. Besides, the dimensionality of this problem, 20, is also high.

The objective functions, both electricity consumption and capital cost, are nonlinear, and it's highly multimodal since for each feasible topology, the component and control variables can be optimized on a local minimum. Therefore, a gradient–ascent algorithm is not proper for this problem. The problem is also highly constrained since the selections of all variables are confined to specific ranges and constraints are imposed to ensure that the systems operate within practicable thermal limits.

For such mixed-integer, high-dimensionality, nonlinear, multimodal optimization problems, genetic algorithms might be suitable heuristic solvers(Mitchell 1998). The successful applications of GA in this kind of optimization problems have also been stated the literature review. Additionally, for a two-objective optimization problem, Non-dominated Sorting Genetic Algorithm II (NSGA-II)is used to search the solution trade-offs between these two objectives.

5. Case study and parametric analysis

This proposed design optimization procedure was validated with real data from a 420-meter-tall landmark skyscraper in Shanghai. It has 88 floors; the lower 50 floors

with 123,000 m2 of space are offices, and the floors from 53 to 88 are a 5-star hotel. Floor 51 and 52 are non-air-conditioned mechanical rooms.

A simplified diagram of the water-side HVAC system is shown in Figure 6, in which six large centrifugal chillers with capacities of 4220 kW (1,100 ton) and two small centrifugal chillers with the capacities of 1406 kW (400 ton) supply cooling. All of these chillers are located in one plant station at the bottom of this building. The chilled-water distribution system consists of two vertical loops separated by heat exchangers on floor 51. Hence, the corresponding topology variables for this system are (1,1,0,0). The design pressures of these two loops are both 2.8 Mpa. Hence, the design variable vector for the actual system is (4, 6, 12, 2, 0, 6, 1, 6, 11, 0, 0, 0, 5.5, 32, 16, 1, 1, 0,0, 5).

Figure 6. Schematic of the HVAC system on the water side

Before optimization, we used sub-metering data and weather data from July 2014 to Oct. 2014 to validate this configuration model. A comparison between the measured and the simulated monthly energy consumption (in cooling season, from May to August) is presented in Figure 7. The total relative errors between real and simulated consumptions of cooling towers, pumps, electrical chillers and AHUs, are 3.68%, -1.2%, 4.9%, and 2.4%, respectively.

With a relative error less than 5%, the simulation model is suitable for optimization. In this case study, we first performed a multi-objective optimization; we then draw general conclusions about HVAC water system design in supertall buildings by conducting a parametric analysis to explore the influence of several uncontrollable parameters on the optimal solution.

Figure 7. Comparison of measured and simulated energy consumption

5.1. Optimization results

When the design pressure is high, if one vertical zone is sufficient to fulfill the hydraulic pressure created by height, it will help avoid the capital cost of any additional set of heat exchangers and pumps, and also avoid loss of chilled-water quality in the upper floors, reducing operation cost; however, it will require additional investment in existing equipment to withstand the high pressure. The optimization calculates this trade-off and the procedure considers both annual electricity cost and capital cost.

NSGA-II was used to search the Pareto Front, whose trade-off property ensures that a decrease in annual energy consumption from one point to another occurs only with a gain in capital cost. Figure 8 shows the results. Because of the discontinuity in design variables, this Front is discontinuous as well. In the Front, three types of topologies, whose row vectors are (1,0,1,2,1), (1,0,1,1,2) and (1,0,1,0,3), respectively, were selected from all solutions. Compared with the real design topology (1,1,0,0,5), which has only 1 plant station, all of the topologies in the Front have 2 plant stations.

Figure 8. Pareto-optimal front for the design optimization problem

Table 4. Comparison of electricity usage between an optimal solution and the baseline

For Jinmao Tower, a mixed-use commercial building, this means that the best water system topology should have 2 plant stations to accommodate different schedules in different functional zones. The optimality of all solutions in the Front can be justified by comparing with the actual design. The capital cost was \$7,270,000, and annual electricity consumption of actual design is 7,550,000 kWh (purple point in Figure 8), while all of the points in the Front were located in the third quadrant, which means they are better in terms of both objectives. The detailed comparisons between one optimal system and the baseline system are listed in Table 4, which shows that the electricity consumption of the four sets of major component of the optimal systems are much less than the baseline system. Additionally, the capital cost of this optimal system is about \$3,570,000, which is also significantly less than the baseline system.

In addition, we observe that each topology in the Pareto Front has limited length and width, which means that the topology has limited the optimization results. This informs us that a reasonable selection of upper topology is necessary when sizing and parameter setting is performed. For example, if HVAC engineers first predefine the topology as (1,0,1,2,1), they will obtain an optimal result near 5,440,000 kWh when regarding only the electricity cost as the objective function. However, if they predefine the topology as (1,0,1,0,3), they will obtain no result better than 5,680,000kWh.

5.2. Parametric Analysis

Using the optimization tool, we can draw some general conclusions about HVAC water system design in a supertall building by analyzing the influences on the optimization results of building function, location, and height. These three parameters have different values as shown in Table 5 The objective function in this analysis is the sum of capital cost and electricity bills for ten years.

Table 5. Values for three parameters

5.2.1 Influence of building function on design optimization

To understand how the function of a supertall building influences water system design, we ran the optimization problems with the same parameter values but different building function values. Three types of functions were considered: office building (O), hotel (H) and office/hotel building (O/H). The major difference between an office building and hotel is the schedule and building load. Table 6 describes how the building function affects the topology of the water system of a 400 m-high building located in Shanghai.

Table 6 shows that in an optimal design, the number of plant stations is relevant to the building function. When the building has a single use, one plant station is sufficient to minimize the objective function, for example, the topology row vector (2,1,1,3) for an office building or hotel; however, mix-used building should have multiple plant stations, for example, the topology row vector (2,2,1,3) for an office/hotel building. The major reason is that in a single-used building, the schedule is relatively uniform, but in a mix-used building, different zones have different schedules.

From these results, useful design rules can be drawn as follow. The number of chiller stations should be decided according to the vertical function sections of this buildings. That is, if there are two vertical function sections which are operated under different schedules, the water system is suggested to have two chiller stations serving these two vertical sections, respectively.

Table 6. Building function's influence on design optimization

5.2.2. Influence of building location on design optimization

In this section, we describe the optimizations we ran after merely changing the building location. The other two parameters were 400 m and office building. The locations of the building were set as Shanghai (SH), Guangzhou (GZ) and Singapore (SIN). Buildings at different locations will have different load profiles through the 8760 hours in a year. The average hourly loads in SIN and GZ are 15.1% and 17.7% larger, respectively, than in SH.

Table 7 lists the optimization results for the building in different locations. The variables $x1$~$x12$ are explained in Table 2. The buildings located in the three places have the same topology, whose row vector is (1,1,0,0,3). That is, although the building is located in different places, the topology for the optimum system remains the same: 1 plant station and 1 PHX. The design pressure for all three water systems was 2.0 Mpa.

However, the results differ in two aspects: chiller capacity and number. In SH, the building had the smallest chiller size: 3 100 ton chillers, 2 600 ton chillers and 5 1100 ton chillers; SIN needed 4 100 ton chillers, 1 600 ton chiller and 6 1100 ton chillers. Therefore, the building location results in different chiller sizes but has little influence on the optimal water system topology.

From these results, useful design rules can be drawn as follow. For the buldings with similar strucutre and function, the optimal system topologies are often the same, which means when designing a new water system, excellent design schemes of similir buildings can be used as reference. Also, it should be noted that although the buildings are similar, the sizing of chiller plants would not always be the same if the buildings are located in different places.

Table 7. Influence of building location on design optimization

5.2.3. Influence of building height on design optimization

In this section, the only controllable variable is the building height. The building location and function were SH and office building, respectively. The corresponding results are listed in Table 8.

It is observed that the optimum topology row vector for the office building in SH is (1,1,0,0), meaning there are 1 plant station and 1 PHX. We note that the higher the building, the larger the system design pressure. As the height increases from 300 to 600 m, the design pressure increases from level 1 (1.6 Mpa) to level 5 (2.8 Mpa). Additionally, as the height increases, the total load of the building also increases, as does the chiller size. The 300 m-high building has one 200 ton chiller, one 600 ton chiller, and four 1100 ton chillers, while the 600 m-high building has six 100 ton chillers, four 1000 ton chillers, and three 1800 ton chillers.

Table 8. Influence of building height on design optimization

Thus, the influence of the building height has two aspects: (1) the building height affects the building load, and thus affects the chiller size; (2) to handle the increased hydraulic pressure caused by increased height, the water system needs more vertical zones or it must tolerate an increased pressure level for the components with an increased capital cost. For a single-function building, more plate heat exchangers are needed to reduce working pressure if there are more vertical zones. This increases the chilled water temperature on the upper floors and raises the operations cost. Through minimizing the sum of the capital cost and 10-year operations cost, we found that the use of two heat exchangers and three sets of pumps is cost effective, and increasing the pressure level of the equipment (e.g., level 2 to level 5) is most cost-effective.

From the above analysis, it can be concluded that when the location and function of buildings are kept unchanged, the HVAC engineer can increase working pressure rather than create more vertical zones through the use of plate heat exchangers when the building height increases.

6. Discussions and Conclusions

A computational procedure to find optimal solutions of HVAC chilled water systems has been proposed, which we believe is the first of its kind since to date almost all system are designed in experience-based manners. This procedure can be formulated as three design sections: the design of HVAC water system topologies, component sizing, and control setting, among which the design of system topologies is the most tricky part.

The simplification of system topologies turns out to a tradeoff between algorithm performance and computation cost since a complex graphic representation of system layout will definitely increase the computation effort exponentially while a simplistic representation will degrade the reliability of solution to great extent. According to the research of [UA], it was found that AHUs and chillers play major parts in the water system. Therefore, only chillers and AHUs are considered as control variables when modeling topologies and marginal components(e.g. pumps, pipes,etc.) are automatically added according to the assumption on the relative position of them. Besides, since PHXs are essential parts in vertical chilled water distribution system, PHXs are also regarded as major components for the design of topologies. Also, two more assumptions with regard to the number of chiller stations and PHXs are made to reduce the computation effort,

The optimality of the generated solutions by this optimization procedure has been examined in the study of a supertall building in Shanghai, which suggests the generated solutions are superior than existing systems in terms of both electricity consumption and capital cost. Besides, parametric analyses have been conducted to get insight into the relationship between the optimal solutions and uncontrolled variables, specifically building function, building locations, as well as building height. This parametric analyses are aimed to provide valuable design rules for system designers since it is still time-consuming and sophisticated to perform such an optimization procedure for designers. It is found that multiple plant stations are suggested when the supertall building has mixed-use, and the HVAC engineer can increase working pressure rather than create more vertical zones through the use of plate heat exchangers when the building is too high. It also turns out that building location has little influence on the optimal water system topology.

There are some limitations in this pilot study. First, the topology models have been simplified to reduce computation efforts. However, the rapid development of distributed computing in recent years might make a detailed graphic modeling of water system layout computationally viable, and this is also the next-step research of us. Second, only primary/secondary pump systems were considered due their wide application in water systems of supertall buildings. But this might overlook some valuable design rules, the research considering other kinds of systems (e.g. primary system) need to be conducted in future.

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Nomenclature

Δp	Pressure difference
k	Pressure resistance coefficient
m	Mass flow rate
C	Capital cost
a	Coefficient vector for polynomial curve
x	Independent variables
J	Objective function
P	Power
I	User defined function
T	Temperature
ϵ	Tolerance
L	Cooling/heating load
CT	Cooling Tower
AHU	Air Handling Unit
VFD	Variable Frequency Driver
PHX	Plate Heat Exchanger
SA	Supply Air
DH	Dissatisfied Hours
WP	Working Pressure
NV	The Number of Vertical zones
H	Height or Head
Cap	Cooling/Heating Capacity
Subscripts	
min	Minimum value
SAT	Supply Air Temperature
chi	Chiller
des	Design condition

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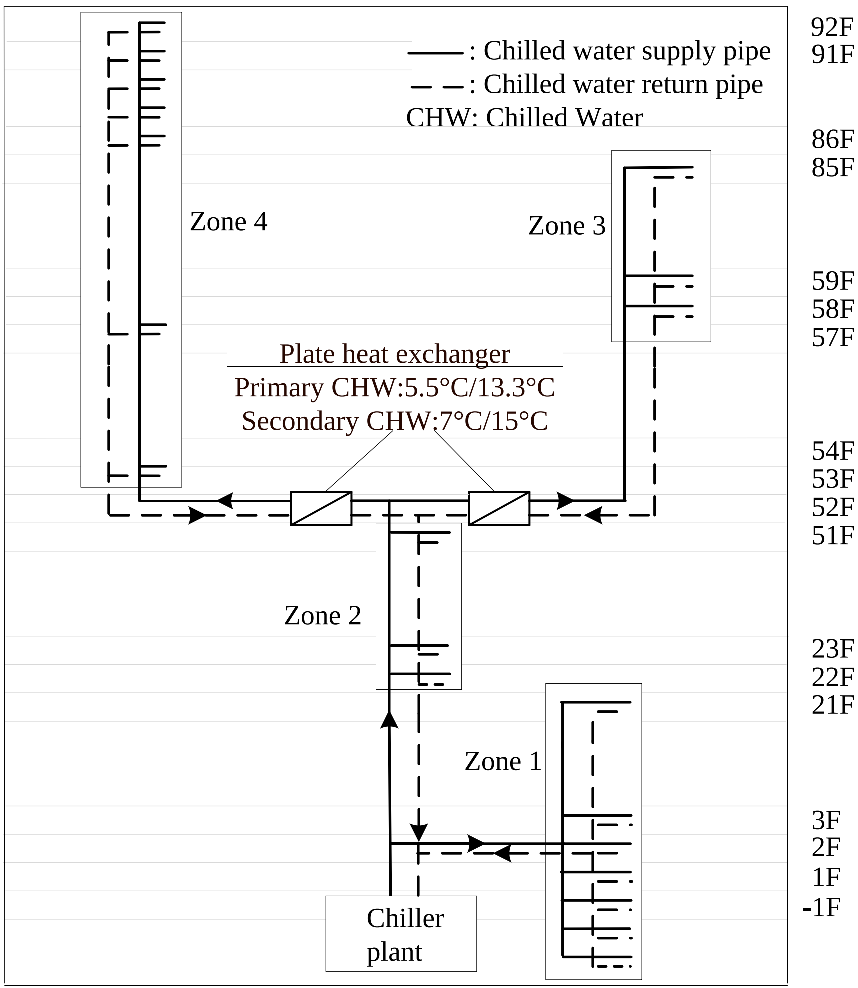


Figure 1. Schematic of an HVAC water system in a supertall building

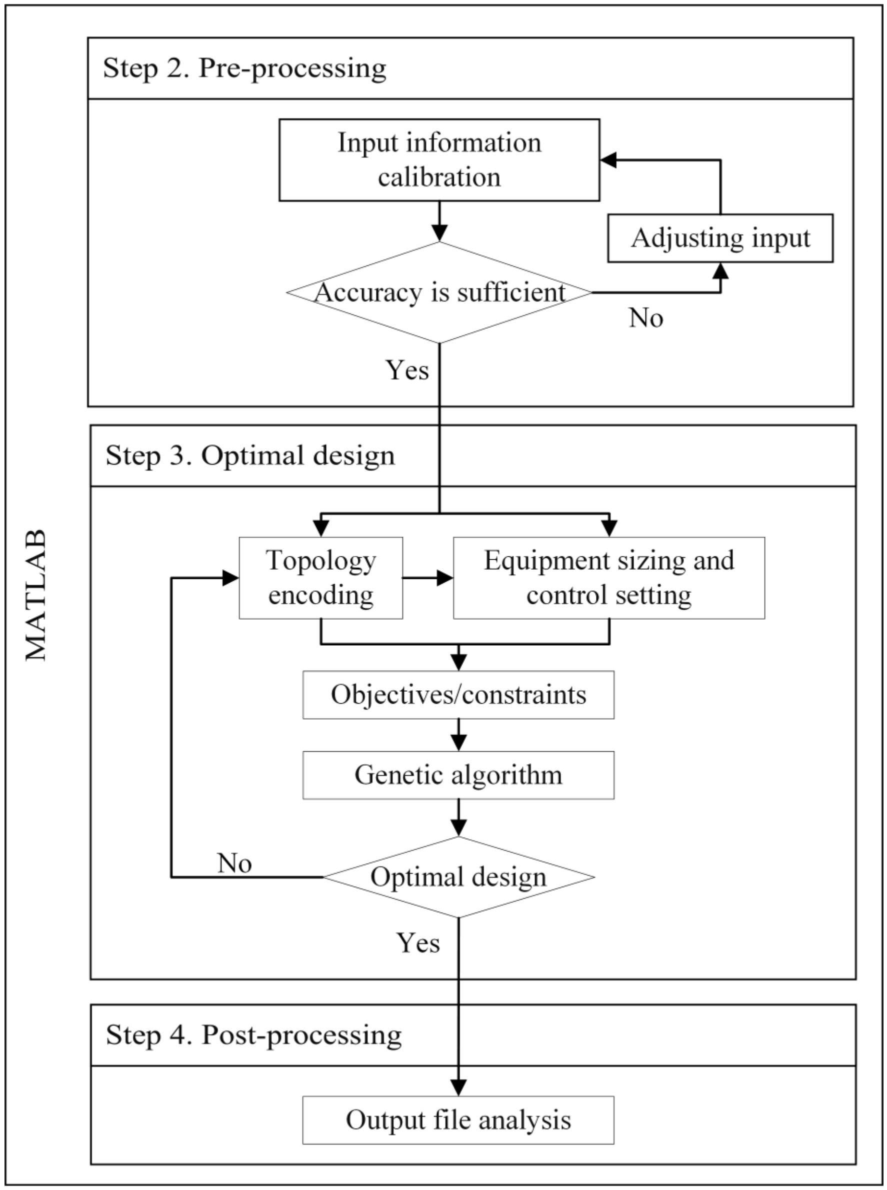
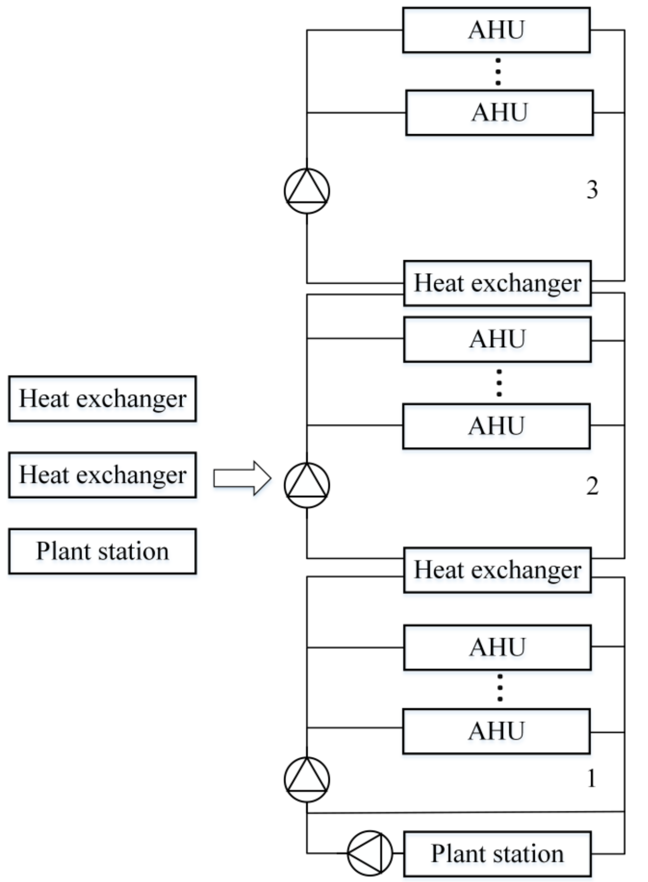


Figure 2. Procedure of optimal design method



(Note: One AHU for each floor)

Figure 3. (left) A permutation for $n_{station} = 1$ and $n_{PHX} = 2$; (right)Topological connection of this permutation

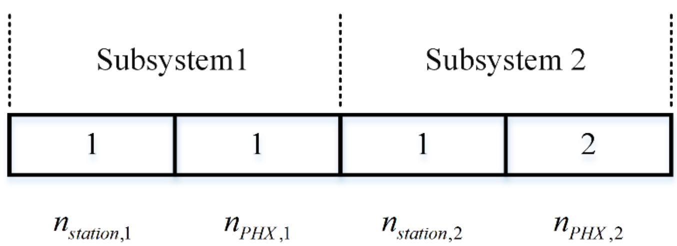


Figure 4. example encoding vector

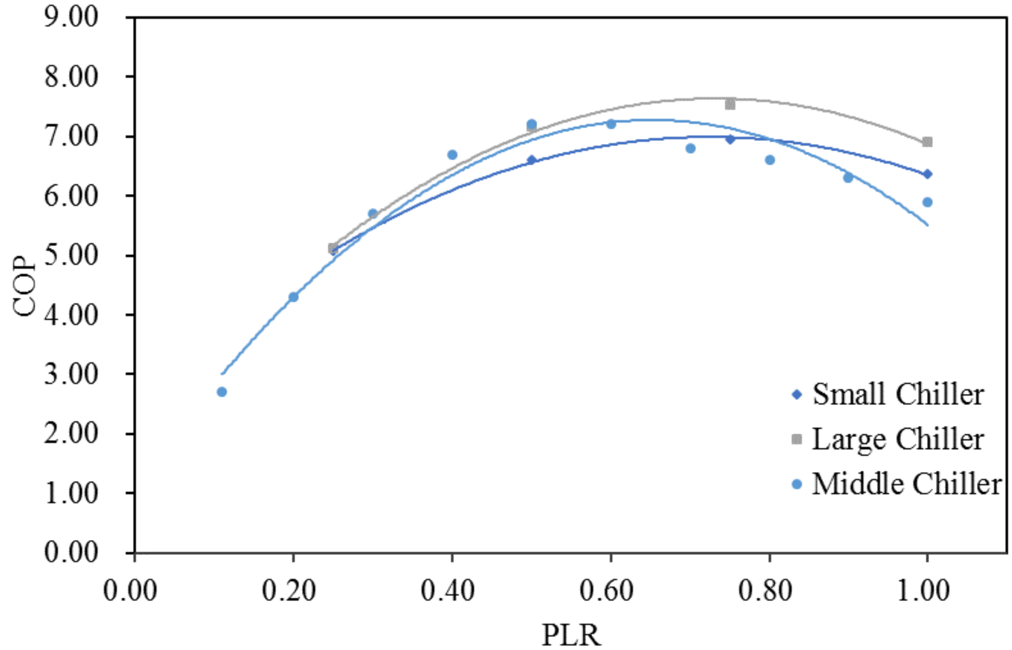


Figure 5. Three sizes of chillers with different COP~PLR curves

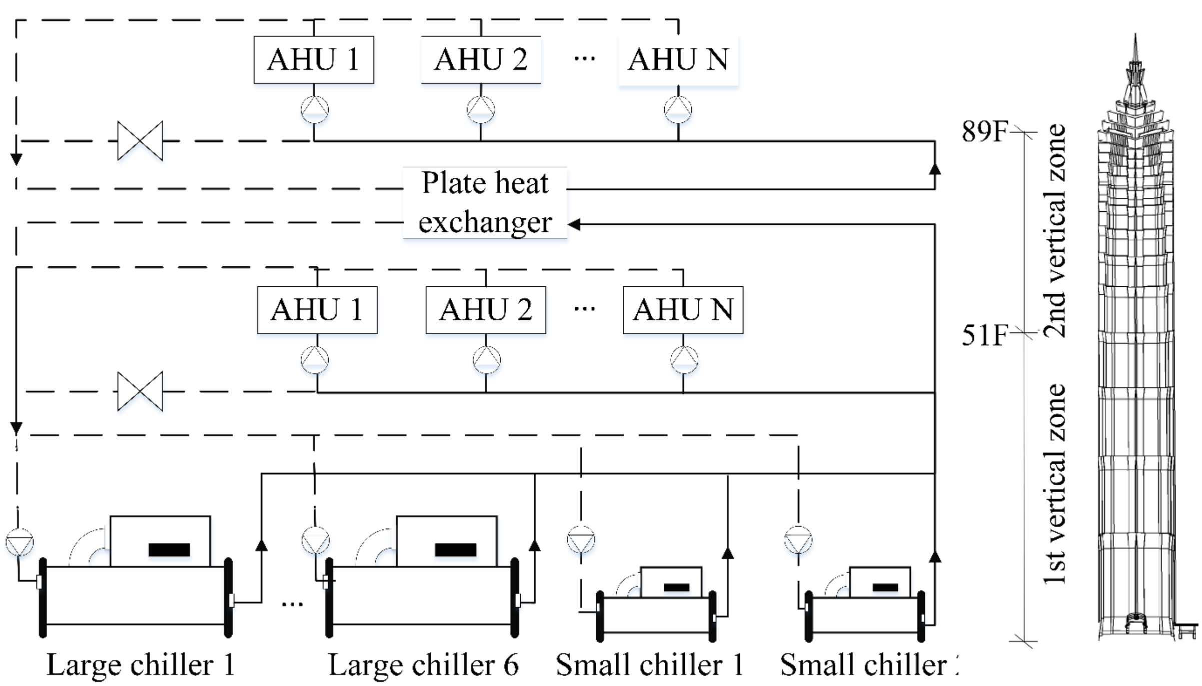
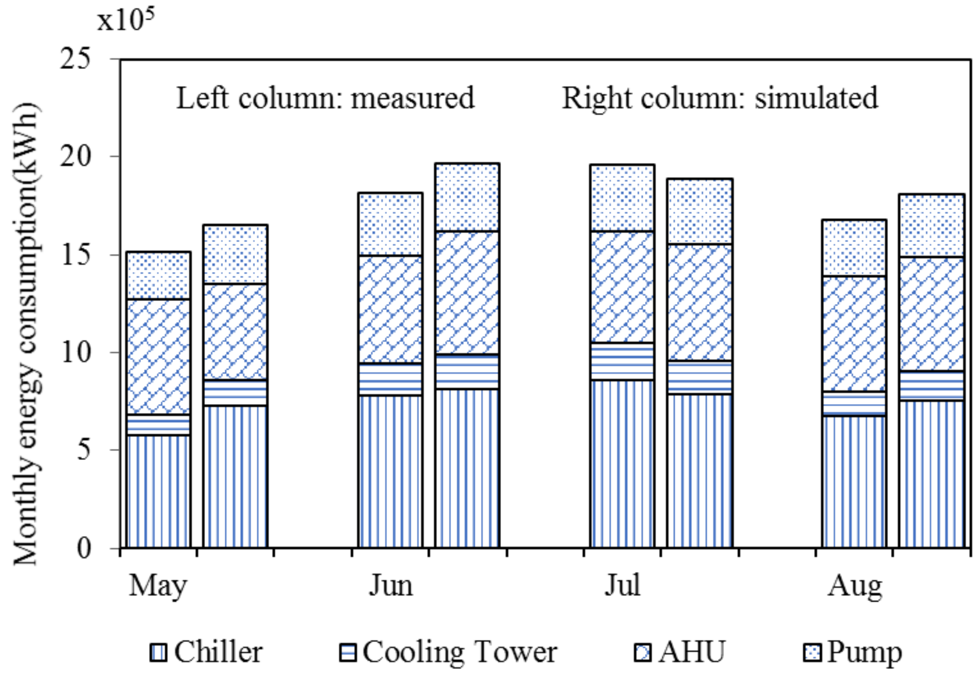


Figure 6. Schematic of the HVAC system on the water side



524 Figure 7. Comparison of measured and simulated energy consumption

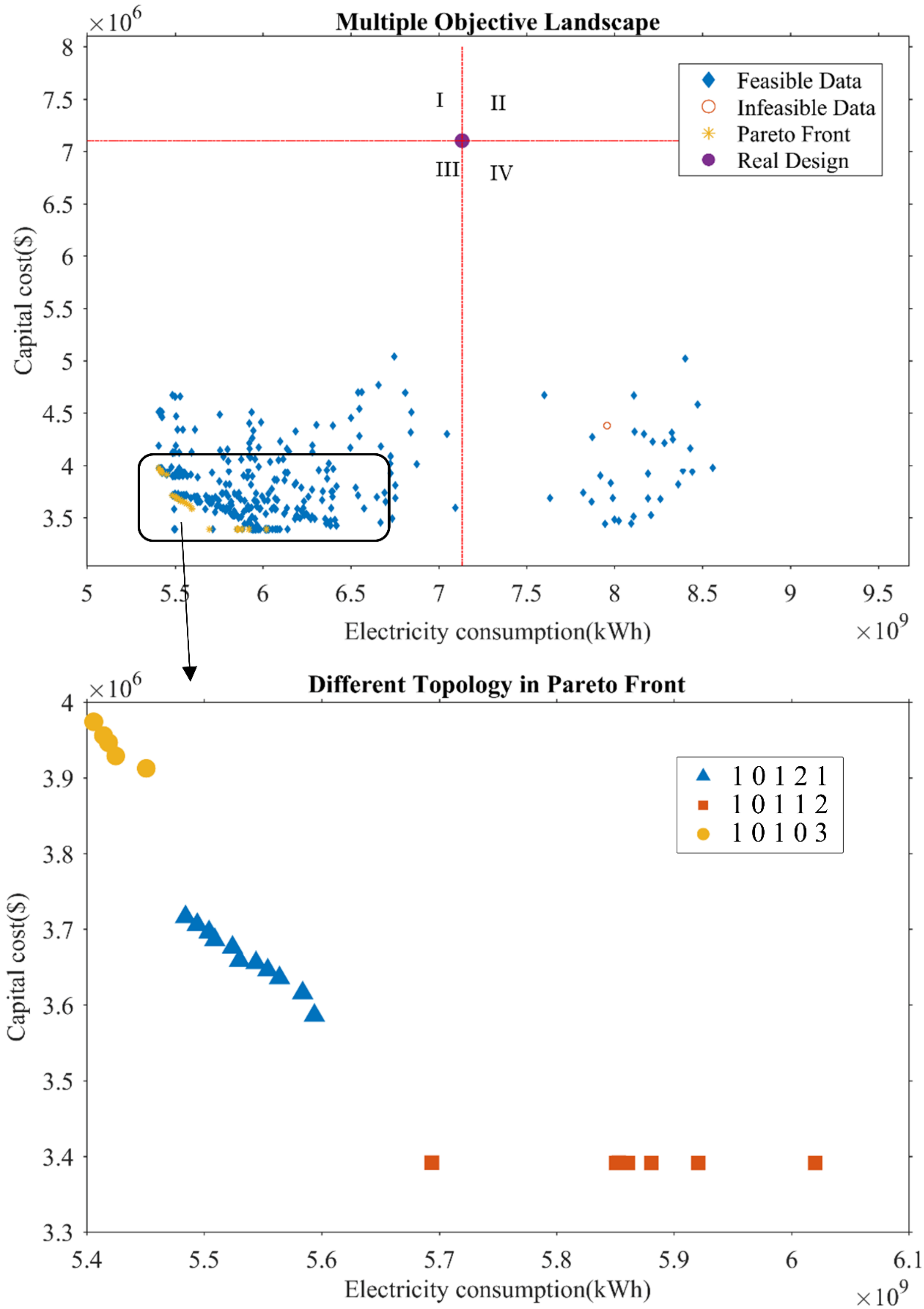


Figure 8. Pareto-optimal front for the design optimization problem

Table 1. Capital cost models for some components				
Component	$\vec{a}$	R^2	***x*(dimension)**	**Range**
Chiller	[-13585,453.64,0]	0.992	Capacity, ton	[40,2500]
Pump	3700[1.0582,10.759,-14.888]	0.956	Design Flow, m^3/s	[0.002,0.1]
PHX	34800[0.0622,37.664,-66.756]	0.996	Design Flow, m^3/s	[0.02,0.2]
CT	[4127.4,122.7,0]	0.992	Capacity, ton	[50,1000]
AHU	4150[0.7569,0.7154,0]	0.998	Design Flow, m^3/s	[0.75,36]
VFD	[1783.5,177.33, -0.2995]	0.987	Design Power, *hp*	[3,200]

Table 2. Design variables in the HVAC water system design optimization					
Variable category	**Variable index**		**Design variable**	**Range & step (dimension)**	**Variable type**
Component variable	Plant station 1	x_1	Design capacity of small chiller	[1,5] & 1 (100 ton)	Integer
		x_2	Design capacity of middle chiller	[6,10] & 1 (100 ton)	Integer
		x_3	Design capacity of large chiller	[11,20] & 1 (100 ton)	Integer
		x_4	Number of small chillers	[0,6] & 1 (--)	Integer
		x_5	Number of middle chillers	[0,6] & 1 (--)	Integer
		x_6	Number of large chillers	[0,6] & 1 (--)	Integer
	Plant station 2	x_7	Design capacity of small chiller	[1,5] & 1 (100 ton)	Integer
		x_8	Design capacity of middle chiller	[6,10] & 1 (100 ton)	Integer
		x_8	Design capacity of large chiller	[11,20]& 1(100 ton)	Integer
		x_{10}	Number of small chillers	[0,6] & 1 (--)	Integer
		x_{11}	Number of middle chillers	[0,6] & 1 (--)	Integer
		x_{12}	Number of large chillers	[0,6] & 1 (--)	Integer
Control variable	x_{13}		LCHWT set point	[5,9] & 0.1 (℃)	Continuous
	x_{14}		ECWT set point	[28, 35] & 0.1 (℃)	Continuous
	x_{15}		SAT set point	[13, 16] & 0.1 (℃)	Continuous
Topology variable	x_{16}		Number of plant stations in subsystem 1	[0,1] & 1 (--)	Integer
	x_{17}		Number of PHXs in subsystem 1	[0,2] & 1 (--)	Integer
	x_{18}		Number of plant stations in subsystem 2	[0,1] & 1 (--)	Integer
	x_{19}		Number of PHXs in subsystem 2	[0,2] & 1 (--)	Integer
	x_{20}		Design pressure level	[1,5] & 1 (--)	Integer

Table 3. Design pressure level and reference value	
Pressure level (simulation input)	**Design pressure value（MPa）**
1	1.0
2	1.6
3	2.0
4	2.5
5	2.8

Table 4. Values for three parameters				
Parameter name	**Parameter name**			
Building function	Office/Hotel(O/H)、Office(O)、Hotel(H)			
Building location	Shanghai(SH)、Guangzhou(GZ)、Singapore(SIN)			
		SH	**GZ**	**SIN**
	Cooling degree days	**1158**	**2036**	**3537**
	Heating degree days	**1599**	**402**	**0**
Building height	300 m、400 m、600 m			

Table 5. Comparison of electricity usage between an optimal solution and the baseline		
Item	**Optimal system(kWh)**	**Baseline (kWh)**
Chiller	2269012	3306050
AHU	803120	120452
Cooling tower	1923124	2753061
Pump	605001	1370436.89

Table 6. Building function’s influence on design optimization		
Building function	**Topology vector**	**Description**
O/H	[1 0 1 0 3]	2 plant stations (one for each subsystem),0 PHX, design pressure 2.0 MPa
O	[1 1 0 0 3]	1 plant stations, 1 PHX, design pressure 2.0 MPa
H	[1 1 0 0 3]	1 plant stations, 1 PHX, design pressure 2.0 MPa

Table 7. Influence of building location on design optimization																	
City	**Component variable**												**Topology variable**				
	*x*1	*x*2	*x*3	*x*4	*x*5	*x*6	*x*7	*x*8	*x*9	*x*10	*x*11	*x*12	*x*16	*x*17	*x*18	*x*19	*x*20
SH	1	6	11	3	2	5	3	6	9	0	0	0	1	1	0	0	3
GZ	1	6	11	4	2	5	3	6	16	0	0	0	1	1	0	0	3
SIN	1	6	11	4	1	6	3	9	11	0	0	0	1	1	0	0	3

Table 8. Influence of building height on design optimization

Height (m)	Component variable												Topology variable				
	*x*1	*x*2	*x*3	*x*4	*x*5	*x*6	*x*7	*x*8	*x*9	*x*10	*x*11	*x*12	*x*16	*x*17	*x*18	*x*19	*x*20
300	2	6	11	1	1	4	4	10	11	0	0	0	1	1	0	0	2
400	1	6	11	4	2	5	3	6	16	0	0	0	1	1	0	0	3
600	1	10	18	6	4	3	2	6	13	0	0	0	1	1	0	0	5