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Optimal design of data center cooling systems concerning multi-chiller system configuration and component selection for energy-efficient operation and maximized free-cooling

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Abstract: The large data center electricity consumption is a growing global concern. To be environment-friendly and to enhance energy efficiency in operation, data center cooling systems adopt a variety of advanced cooling and renewable energy technologies such as free cooling. However, these free cooling systems are not optimally designed in field practices, and their energy efficiencies are much lower than that of the ideal case. In this study, optimal designs in water piping, pumps and equipment sequencing control are introduced to maximize the cooling efficiency of free cooling systems. It finds that the use of distribution headers around cooling towers and pumps, the maximization of the number of operating cooling towers, the minimization of the number of operating pumps and the mixed use of large and small single-speed pumps can reduce the system's power consumption by 60% under certain operating conditions. The results also show that the designs can reduce the annual energy consumption by 3 to 15% depending on the climate conditions.

Keywords: data center cooling; free cooling; energy efficiency; optimal design; optimal control

1. Introduction

The growing energy consumption of data centers has attracted lots of attention in recent years, and businesses have implemented various measures to reduce their energy cost. Shehabi et al. reported that data centers consume 1.8% of electricity generated in the U.S. in 2014, and their electricity consumption grew at 4% annually [1]. According to the

Natural Resources Defense Council (NRDC), the potential to reduce the energy cost of data centers in the U.S. in 2014 is around USD$3.8 billion [2]. Ascierto reported that the data center industry has reduced their average power usage effectiveness (PUE), an indicator of the efficiency of data centers, from 2.5 in 2007 to 1.65 in 2013, revealing significant improvement in the energy efficiency of data centers [3]. One major driver of the change is the research in data center cooling technologies. Since approximately 40% of data center energy consumption comes from their cooling systems [4] and energy use of data center cooling systems is the main cause of high PUEs in data centers [1], research for energy efficiency of data center cooling systems is growing rapidly to reduce the overall electricity consumption of data centers. New technologies such as underfloor air distribution, air containment, free cooling by economizer, variable-speed technologies, direct current power distribution, liquid-cooled information and communication technology (ICT) equipment and thermosyphon cooling have been developed to reduce energy use of data center cooling systems [5]–[9].

While the energy saving potentials of the novel technologies have been widely investigated, the energy saving potentials in their interaction with other equipment in multi-chiller systems are not. This type of studies was conducted with conventional cooling systems only. For example, Braun proposed the use of different sequencing controls for pumps and chillers enabled by alternative piping configurations to reduce energy use in multi-chiller systems [10]. Li and Wang studied how to mitigate pump oversizing issue by a probabilistic optimal design method to design the pumps in a multi-chiller system [11]. There is also other research that investigates various methods to optimize sequencing controls of chillers and cooling towers in conventional multi-chiller systems [12]–[16].

However, for water-side free cooling systems in data center cooling systems, few research projects were conducted on its design to optimize the energy efficiency of systems with water-side free cooling systems. Lui has studied the capability of different piping configurations of indirect water-side free cooling systems in data center cooling systems with one economizer [17]. Griffin described how a data center cooling system with water-side economizers conducted control sequencing of the equipment to optimize its cooling system by maintaining a constant temperature difference across water supply and return at all loads [18]. Taylor suggested the use of more cooling towers than necessary and higher chilled water pump head for the operation of the water-side economizers [19]. Zhang et al. reviewed multiple literature that improved water-side free cooling system design using additional cooling source and solar cooling systems [20]. Little research has concerned with how designs of system configuration and component sizing are coordinated with multiple system sequencing and free cooling to maximize the overall energy efficiency of data center cooling systems under different climate and weather conditions. This leads to free cooling systems operating with lower energy efficiency than the ideal case in the field.

This paper presents an optimized design of data center cooling system involving indirect free cooling systems and water-side economizers. It involves the design of piping, pump and equipment sequencing control configurations to optimize the energy saving potential of water-side economizers. The optimized design is identified by comparing the performance of a baseline design of a data center cooling system with four alternative energy-saving designs in a simulation case study. The comparison is followed by a discussion on why the design is optimal and ends with a study on how it performs in different climate zones. With the optimized design that is not found in previous studies, data center cooling systems with water-side economizers can be designed to optimize the energy saving potential of their water-side economizers and further enhance their energy efficiency than previously built data centers.

2. Indirect free cooling system using water-side economizers

Water-side economizers are important energy-saving technologies in water-cooled data center cooling systems [20], [21]. It is a type of renewable energy technology that uses evaporative cooling to absorb heat from the ICT equipment in data centers directly when the ambient temperature is cold. A schematic of a typical indirect water-side free cooling system is shown in Figure 1 [17].

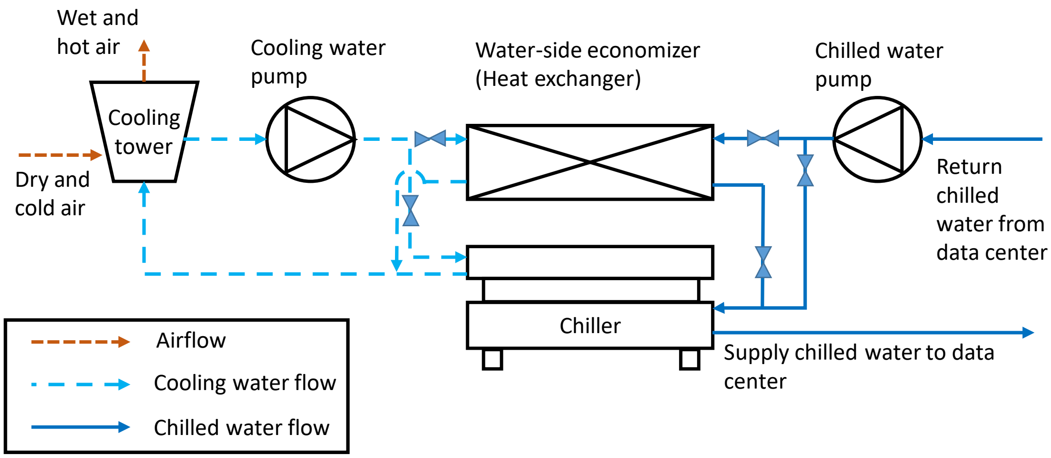

Figure 1 Schematic of a water-cooled data center cooling system with a water-side economizer

The system in Figure 1 can operate in three different modes:

- Mechanical cooling mode
- Partial free cooling mode
- Free cooling mode

When the weather is hot and wet, the system runs in mechanical cooling mode. The chiller operates to absorb heat from the return chilled water so that the temperature of supply chilled water for data center cooling is maintained at its temperature setpoint. The chiller rejects heat to the cooling water, and the heat in the cooling water is dissipated to the ambient by evaporative cooling at the cooling tower. The cooling water from the cooling tower remains hotter than the return chilled water from the data center, and it does not enter the water-side economizer to avoid heating up the chilled water. When the weather becomes cooler and drier, the cooling water from the cooling tower becomes cooler than the return chilled water from the data center. The system operates in partial free cooling mode, and its water-side economizer operates to pre-cool the return chilled water before it enters the chiller. While the cooling water entering the water-side economizer is not cold enough to cool the return chilled water to the temperature setpoint of the supply chilled water, its pre-cooling of the return chilled water reduces the cooling load at the chiller and reduces the energy consumption of the system. When the weather becomes even cooler and drier, the cooling water coming out of the cooling tower becomes colder than the temperature setpoint of the supply chilled water. It is cold enough to lower the temperature of the return chilled water temperature to the temperature setpoint of the supply chilled water. The system operates in free cooling mode and uses the water-side economizer to keep the supply chilled water temperature at its setpoint. Chiller operation is not needed, the chiller is switched off and the system energy consumption is further reduced. Hence the partial free cooling mode consumes less energy than the mechanical mode, and the free cooling mode consumes less energy than the other two modes. While the theory to switch operation modes for the operation of the water-side economizers is well understood, it is unknown what changes are needed at the other equipment to optimize the system if it has multiple chillers and water-side economizers.

3. Designs with different system configurations for energy-efficient control

This section describes a baseline design that represents a conventional data center cooling system with water-side economizers and four alternative energy-saving designs to study the effect of other designs on energy efficiency of data center cooling systems.

3.1 Baseline Design

The Baseline Design represents data center cooling systems that do not have special piping, pump and sequencing control configurations. Its schematic is shown in Figure 2, and the details of the cooling units in Figure 2 are shown in Figure 3.

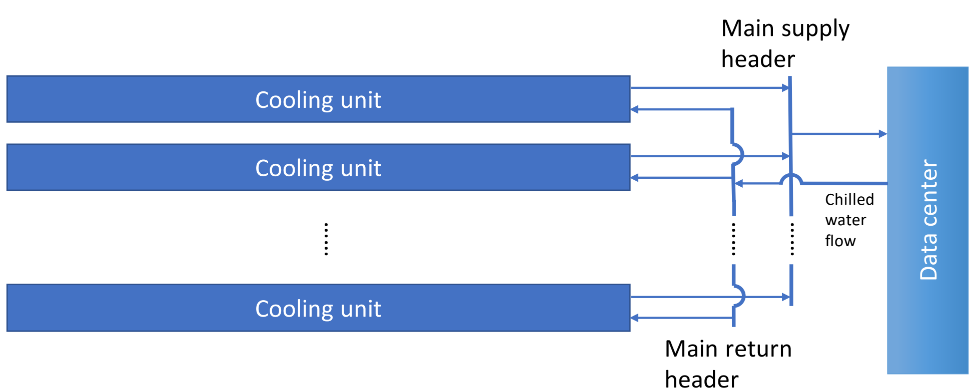

Figure 2 Schematic of a data center cooling system in the baseline scenario

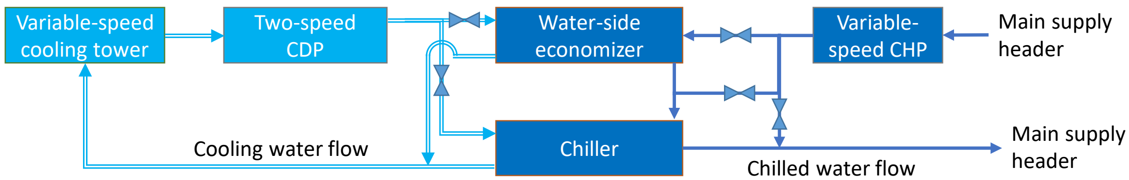

Figure 3 Schematic of a cooling unit in the baseline scenario

Each cooling unit consists of pumps and a cooling tower that are connected in series with a water-side economizer and a chiller. Its variable-speed cooling tower, its two-speed cooling water pump (CDP) and its variable-speed chilled water pump (CHP) must be switched on first before its water-side economizer or chiller can operate for data center cooling. If one of the pumps or the cooling tower fails, the water-side economizer and the chiller cannot operate. This connection implies that the chiller or water-side economizer in each cooling unit can only operate if its cooling towers, its chilled water pumps and cooling water pumps are normal.

While the connection does not allow any of the pumps or the cooling tower to be switched off during operation, it permits the water-side economizer and the chiller to operate separately. There are distribution headers around the two equipment that the water flow to one of them can be stopped without obstructing the water flow to the other equipment. Having a chiller and water-side economizer that require similar cooling water flow rates, the cooling unit in Figure 3 uses a two-speed cooling water pump that supports the simultaneous operation of a chiller and a water-side economizer at its full speed and supports the operation of either one of them at a lower speed. The chilled water pump is designed to be variable-speed based on the conventional primary-pump-only cooling system [22]. The cooling tower also has a variable-speed drive to control the speed of its fan. Unlike the mechanical cooling mode and partial free cooling mode which the chilled water temperature at the supply is controlled by the chiller, the free cooling mode does not have any chiller to control the supply chilled water temperature. To ensure that the temperature remains at the setpoint and will not be too low for any condensation issue in the data centers, a variable-speed drive is used at the cooling tower to control the fan speed to control the water temperature at the main supply header.

3.2 Alternative Design 1

The first alternative design is made based on ASHRAE (2016) [14] which contains distribution headers around all cooling towers in a data center cooling system as shown in Figure 4. This setting allows the number of operating cooling towers to be different from the number of operating chillers and the number of operating water-side economizers. This design permits the use of more cooling towers than chillers and water-side economizers than conventional systems. It increases heat rejection area in the evaporative cooling process at the cooling towers for higher efficiency of the data center cooling system.

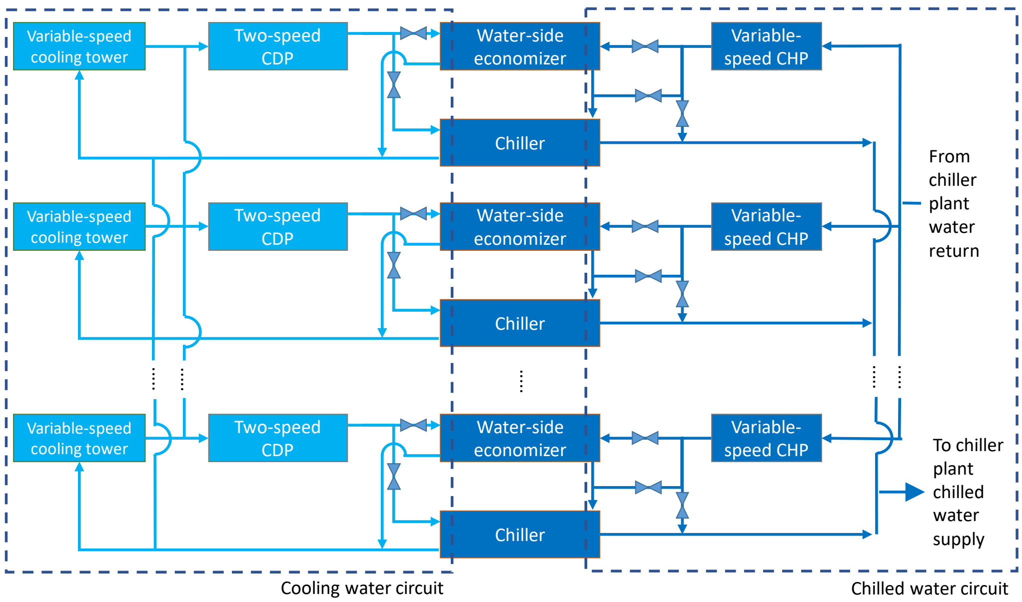

Figure 4 Schematic of Alternative Design 1

In this design, the number of operating cooling towers is set by Equation (1).

$$N_{op,ct} = \max\left(\max\left(N_{op,ch} + N_{op,hx}\right) + 1, N_{ct}\right) \quad (1)$$

where $N_{op,ct}$ is the number of operating cooling towers, $N_{op,ch}$ is the number of operating chillers, $N_{op,hx}$ is the number of operating water-side economizers, N_{ct} is the number of cooling towers installed.

Equation (1) controls the number of operating cooling towers so that it is larger than the number of operating chillers and water-side economizers. Theoretically, all cooling towers should be switched on to maximize the number of operating cooling towers and the heat rejection area. This may cause issues in the water level in the cooling towers or even lack of water in operating cooling towers, and thus the control in this study only increases the number of operating cooling towers slightly to avoid the issue.

3.3 Alternative Design 2

The second alternative design is based on the piping configuration and the sequencing control algorithm in Braun [10]. The study found that the water flow rate required at the chillers is lower when a multi-chiller system is running at part-load conditions, and the multi-chiller system can become more efficient by reducing the number of operating pumps. To run a multi-chiller system with lower water flow rate, it suggested to install distribution headers around the pumps to reduce the number of operating pumps during part-load conditions.

To use the method in a data center cooling system with water-side economizers, Alternative Design 2 contains distribution headers around the cooling water pumps in addition to the distribution headers in Alternative Design 1 as shown in Figure 5. In this design, distribution headers are installed around the two-speed cooling water pumps, and the system can run fewer cooling water pumps than the number of operating water-side economizers and chillers. When the total water flow rate required by the water-side economizers and chillers can be satisfied by fewer pumps, some pumps can be switched off to lower the energy use of the pumps.

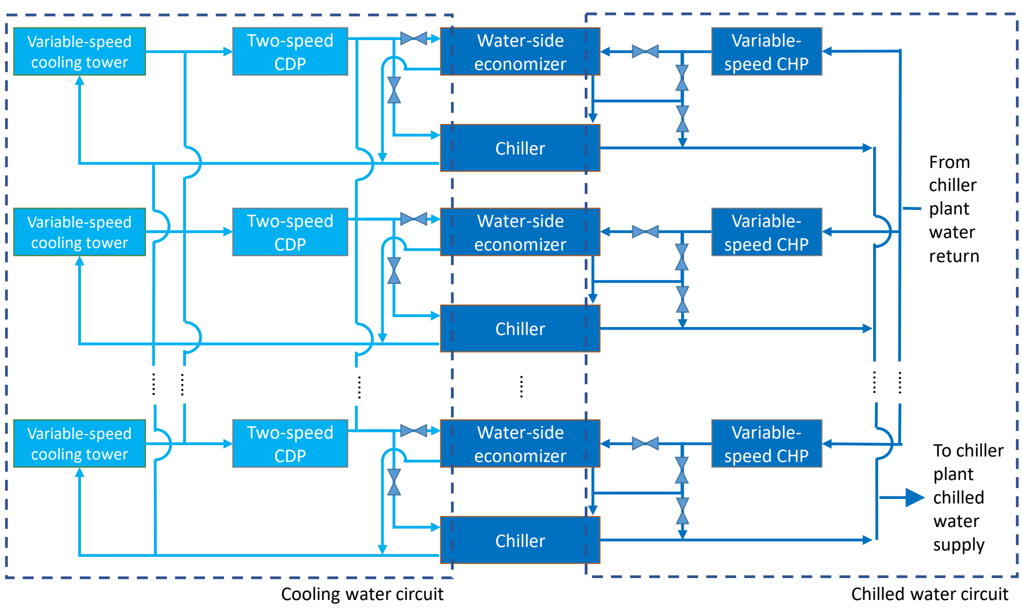

Figure 5 Schematic of Alternative Design 2

3.4 Alternative Design 3

Alternative Design 3 is the replacement of cooling water pumps with smaller constant-speed pumps. In the previous designs, the size of the pumps is designed to operate one chiller and one water-side economizers simultaneously. While this is necessary when the cooling water pumps are dedicated to separate chillers and water-side economizers in the Baseline Design, some pump capacity becomes redundant when the cooling water pumps are bounded by a pair of distribution headers. The data center cooling system is not designed to run all chillers and water-side economizers simultaneously, and the maximum total cooling water flow rate in the previous designs is much larger than the maximum cooling water flow required by the system. Thus the large variable-speed cooling water pumps can be replaced by smaller constant-speed cooling water pumps to avoid oversizing and the resultant inefficiency. By replacing the two-speed cooling water pumps in Alternative Design 2 with smaller constant-speed pumps, Alternative Design 3 is created as shown in Figure 6 [11], [23].

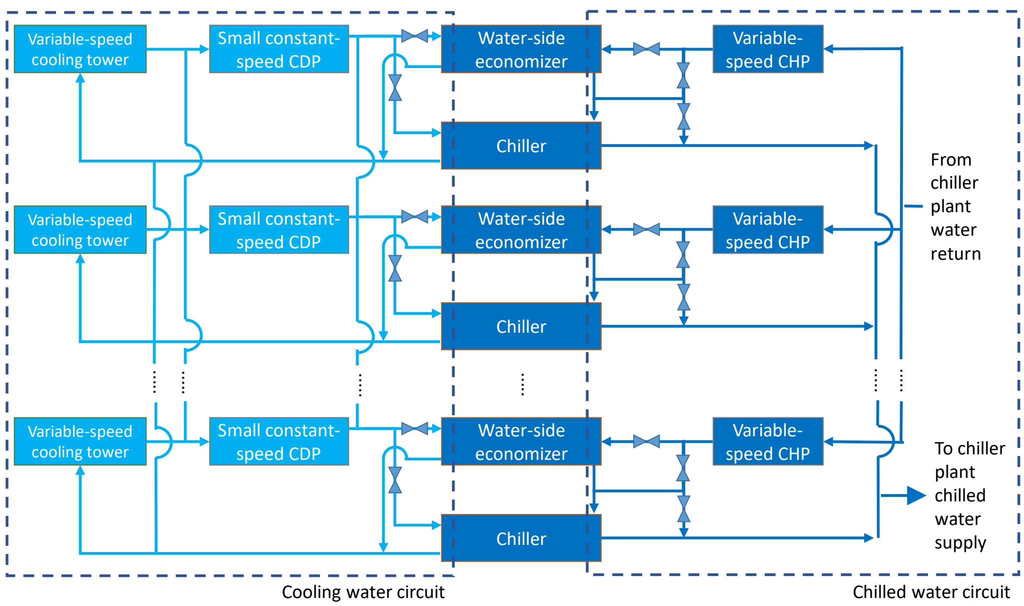

Figure 6 Schematic of Alternative Design 3

Figure 6 shows that the two-speed cooling water pumps in Figure 5 are replaced by constant-speed pumps. These pumps are designed differently from the two-speed cooling water pumps that their rated water flow rate should be the same as the required flow rate of a water-side economizer or a chiller. They run more efficiently than the two-speed pumps at the rated flow rate of the constant-speed pumps. The number of operating cooling water pumps in this design is the same as the total number of operating water-side economizers and chillers, or the cooling water flow rate will not be sufficient for the heat rejection of the data center cooling systems.

3.5 Alternative Design 4

In each of the previous designs, only one type of cooling water pump is used. While they work efficiently at their design conditions, the total flow rate of the cooling water circuit changes and there are always some operating conditions that they fail to run efficiently. Alternative Design 2 uses large two-speed cooling water pumps and is more efficient at large water flows, while Alternative Design 3 uses small constant-speed cooling water pumps and performs better at smaller flow rates. To gain the advantage of both designs, a new design to use constant-speed cooling water pumps of two different flow capacities is proposed in Figure 7.

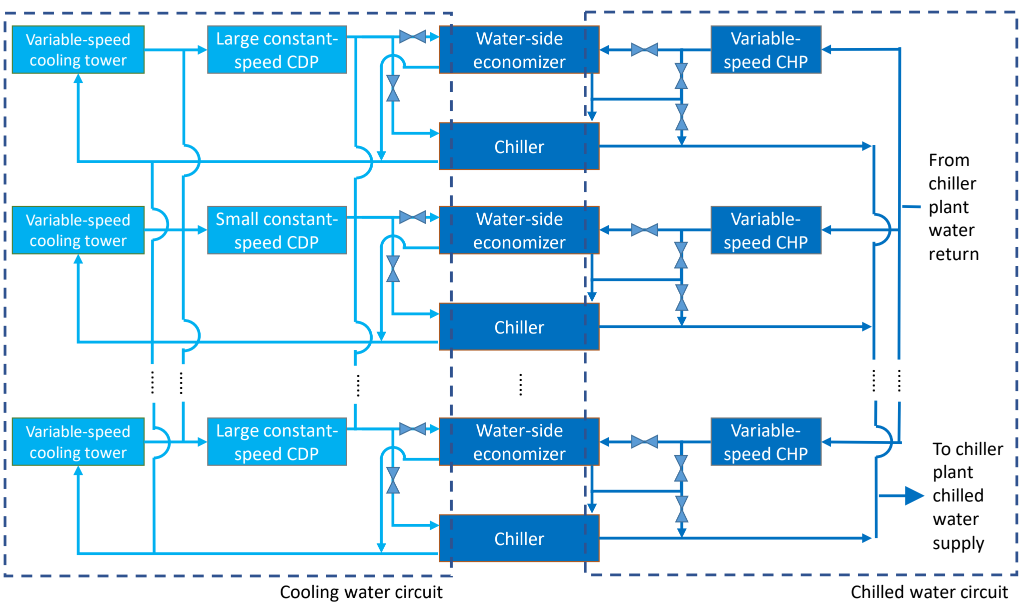

Figure 7 Schematic of Alternative Design 4

In this design, half of the cooling water pumps are constant-speed pumps designed based on the smallest possible flow rate on the cooling water circuit, and the rest are constant-speed pumps designed at the total flow rate required by a water-side economizer and a chiller. All pumps are designed at the same pressure head to avoid water from flowing backwards into a pump. The sequencing control of the pumps is also specially designed to minimize the number of operating pumps to reduce the energy consumption of the data center.

4. Simulation case study

To compare the performance of the Baseline Design with the alternative design and examine if the alternative designs improve system energy efficiency, the designs are used with a data center cooling system in a simulation case study. The simulation case study is built upon the specification of a real data center, control algorithms, mathematical models of the equipment and some environmental conditions. After simulating the operation of the data center systems under various designs and operating conditions as shown in Figure 8 using TRNSYS 18 [24], the energy performance of the designs can be fairly compared.

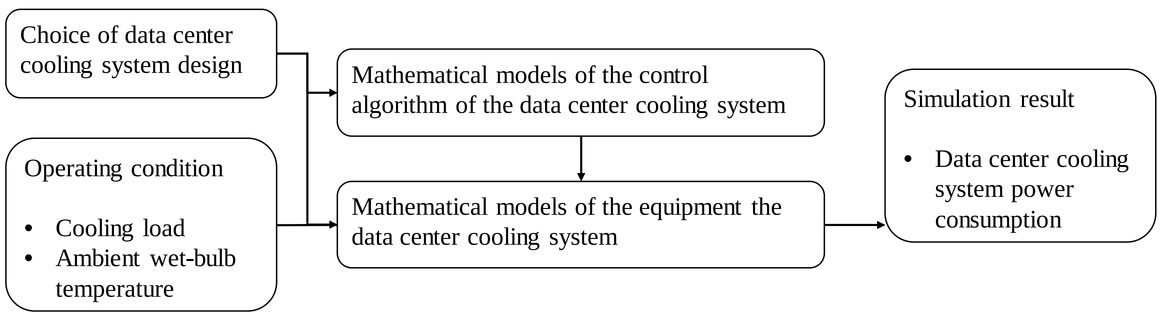

Figure 8 Flowchart to simulate the operation of a data center cooling system with a set of operating conditions

4.1 Specification of the data center

The case study involves a 16,800 kW data center cooling system with four 4,200 kW water-cooled chillers and four water-side economizers with design heat transfer rate at 4,300 kW. The design water flow rates of both equipment are identical at 620,000 kg/h. The detailed specification of the data center cooling system is shown in Table 1.

Table 1 Specification of the data center cooling system in the case study

Equipment	**Design parameter**	**Quantity**
Water-cooled chiller	Design cooling capacity: 4200 kW Design chilled water outlet temperature: 13 °C Design chilled water flow rate: 544300 kg/h Design cooling water flow rate: 620000 kg/h	4
Water-side economizer	Design heat transfer rate: 4300 kW Design water flow rate: 620000 kg/h	4
Variable-speed chilled water pump	Design flow rate: 620000 kg/h Design pressure head: 500 kPa Design power consumption: 110 kW	4
Variable-speed cooling tower	Design power consumption: 74 kW Design heat rejection rate: 16800 kW	4

	Design power for anti-freezing electrical heater: 60 kW	

The different specifications of cooling water pumps in the Baseline and Alternative Designs are listed in Table 2.

Table 2 Cooling water pumps (CDPs) in different designs in the case study

Design	**Design parameter**
Baseline, Alternative Design 1, Alternative Design 2	4 two-speed 145 kW pumps with a design flow rate at 1240000 kg/h and a design pressure head at 350 kPa
Alternative Design 3	4 constant-speed 84 kW pumps with a design flow rate at 620000 kg/h and a design pressure head at 350 kPa
Alternative Design 4	2 constant-speed 145 kW pumps with a design flow rate at 1240000 kg/h and a design pressure head at 350 kPa, and 2 constant-speed 84 kW pumps with a design flow rate at 620000 kg/h and a design pressure head at 350 kPa

The first set of CDP design in Table 2 contains CDPs which can support the simultaneous operation of a water-side economizer and a chiller. If any of the chillers or water-side economizers shuts down and the water flow rate required becomes lower, the pumps run at their low-speed setting for a lower water flow rate. The second set of CDP design in Table 2 is smaller than the first set, and each of them can only run at one speed to provide a 620000 kg/h flow. The third set of CDP design consists of a combination of pumps. It can run a large pump to provide a large flow to support the operation of a chiller and a water-side economizer simultaneously and run a small pump to support the operation of either a chiller or a water-side economizer.

4.2 Control algorithms

The simulation case study also needs a set of control algorithms to simulate the control of operation modes, water temperature, number of operating equipment and speed of equipment in different designs of the data center cooling system.

Operation mode

Since the study investigates the energy saving potential of the designs, the operation mode control is assumed to be ideal. At each operating condition, the data center cooling system is simulated under all three operation modes (i.e. mechanical cooling, partial free cooling and free cooling), and the operation mode that can satisfy the cooling requirement and gives the best performance is selected as the operation mode. The simulation procedure of the operation mode selection process is illustrated in Figure 9.

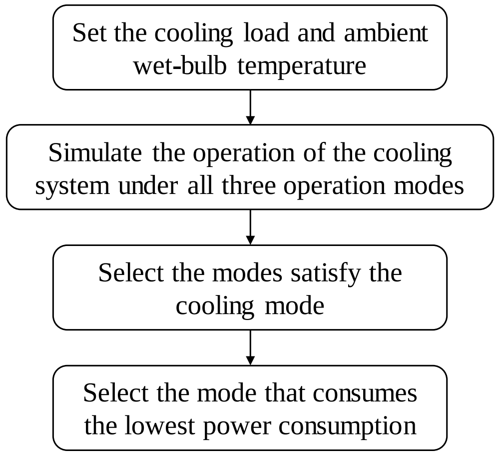

Figure 9 Procedure to select an operation mode in the simulation result

Supply chilled water temperature

The supply water temperature is fixed at 13 °C. When the data center cooling system operates in mechanical cooling and partial free cooling mode, the supply water temperature is achieved by the control of the capacity of the chiller. However, in free cooling mode, the chillers are off, and the speed of the fans at the cooling towers is used to control the supply chilled water temperature at the outlet of the water-side economizer to be 13 °C.

Number of operating chillers and water-side economizers

The control of the number of operating chillers and water-side economizers depends on the operation mode and the cooling load. To satisfy the cooling load, the cooling capacity of all operating chillers and water-side economizers must be greater than or equal to the cooling load. Whether to operate chillers or water-side economizers is determined by the operation mode. Mechanical cooling mode operates the chillers but not the water-side economizers, and vice versa in free cooling mode. The resultant ruleset to determine the number of operating chillers and water-side economizers is shown in Table 3.

Table 3 Ruleset to determine the number of operating chiller and water-side economizers

Operation mode	**Cooling load**	**Number of operating chillers**	**Number of operating water-side economizers**
Mechanical cooling	Lower than 4200 kW	1	0
	Between 4200 kW and 8400 kW	2	

	Between 8400 kW and 12600 kW	3	
	Higher than 12600 kW	4	
Partial free cooling	Lower than 8500 kW	1	1
	Otherwise	2	2
Free cooling	Lower than 4300 kW	0	1
	Between 4300 kW and 8600 kW		2
	Between 8600 kW and 12900 kW		3
	Higher than 12900 kW		4

Number of operating chilled water pumps

The control of the number of operating chilled water pumps does not change between designs because the chilled water pump configuration is not changed in the study. The number of operating chilled water pumps in all designs equals to the maximum between the number of operating chillers and the number of operating economizers as shown in Equation (2).

$$N_{op,chp} = \max(N_{op,ch}, N_{op,hx}) \tag{2}$$

where $N_{op,chp}$ is the number of operating chilled water pumps

Number of operating cooling water pumps

The control of the number of operating cooling water pumps differs between designs. When the cooling water pumps are not bounded by distribution headers (i.e. Baseline Design, Alternative Design 1), all cooling water pumps connected to operating chillers and water-side economizers must operate to support their operation. The number of operating cooling water pumps in these designs equals to the number of operating chilled water pumps calculated by Equation (2).

When the cooling water pumps are bounded by distribution headers (i.e. Alternative Design 2, Alternative Design 3 and Alternative Design 4), the number of operating cooling water pumps is determined by the total required cooling water flow rate as shown in Equation (4).

$$\dot{m}_{req,cdp} = N_{op,ch}\dot{m}_{des,cdw,ch} + N_{op,hx}\dot{m}_{des,cdw,hx} \tag{3}$$

where cdp is cooling water pump and cdw is cooling water flow

Based on the total required cooling water flow rate, the number of operating cooling water pumps can be determined based on the ruleset in Table 5 that is designed to minimize the number of operating cooling water pumps.

Table 4 Ruleset to determine the number of operating cooling water pumps in Alternative Designs 2, 3 and 4

Design	**Total required cooling water flow**	**Number of operating cooling water pumps**
Alternative Design 2	Lower than 1240000 kg/h	1
	Between 1240000 kg/h and 2480000 kg/h	2
Alternative Design 3	Lower than 620000 kg/h	1
	Between 620000 kg/h and 1240000 kg/h	2
	Between 1240000 kg/h and 1860000 kg/h	3
	Higher than 1860000 kg/h	4
Alternative Design 4	Lower than 620000 kg/h	1 small pump
	Between 620000 kg/h and 1240000 kg/h	1 large pump
	Between 1240000 kg/h and 1860000 kg/h	1 large pump and 1 small pump
	Higher than 1860000 kg/h	2 large pumps

Number of operating cooling towers

The number of operating cooling towers is determined based on the number of operating chillers and water-side economizers and the presence of distribution headers around the cooling towers. In the Baseline Design, the cooling towers are not bounded by distribution headers. Each cooling tower connected to an operating chiller and water-side economizer must operate, and the number of operating cooling towers equals to the number of operating chilled water pumps calculated by Equation (2). In other alternative designs which the distribution headers are connected to both inlets and outlets of cooling towers, the number of operating cooling towers is determined by Equation (1).

Speed of pumps

The speed of chilled water pumps is controlled to reach the required total chilled water flow rate from Equation (5) within the speed limits of the pumps at 30 Hz and 50 Hz.

$$\dot{m}_{req,chw} = N_{op,ch}\dot{m}_{des,chw,ch} + N_{op,hx}\dot{m}_{des,chw,hx} \quad (4)$$

where $\dot{m}_{chw}$ is the chilled water flow rate, $\dot{m}_{des,ch}$ is the design chilled water flow rate of the chiller and $\dot{m}_{des,hx}$ is the design chilled water flow rate of the water-side economizer.

The speed of the two-speed cooling water pumps is also controlled in a similar manner that it is controlled to reach the required total cooling water flow rate from Equation (4).

However, if the required speed is higher than the low-speed setting at the two-speed cooling water pumps, the pumps will be set to operate at 50 Hz instead of the required speed.

The speed of constant-speed pumps always remains at 50 Hz.

Speed of the variable-speed fans in the cooling towers

The control of the speed of the variable-speed fans in the cooling towers is determined by the operation mode and the ambient wet-bulb temperature. In free cooling mode, the speed of the fans is controlled so that the supply chilled water temperature of the water-side economizers reaches 13 °C. In partial free cooling mode and mechanical cooling mode, the supply chilled water temperature is controlled by the chiller, and the speed of the fans is used to maintain the cooling tower water outlet temperature at a setpoint given by Equation (6).

$$T_{ct,cdw,out,setpt} = \max\left(T_{amb,wb} + 5[°C], 18[°C]\right) \tag{5}$$

where $T_{ct,cdw,out,setpt}$ is the temperature setpoint at the cooling water outlet of the cooling towers, and $T_{amb,wb}$ is the ambient wet-bulb temperature.

Equation (6) is designed to ensure optimal performance of the fan and the chiller without very low condensing temperature at the chillers [22].

4.3 Mathematical and computational models of the data center cooling system

The operation of the data center cooling system is simulated in TRNSYS 18 [24], and most equipment is modeled by the built-in models in TRNSYS. Chillers were modeled by TRNSYS model Type 142, water-side economizers were modeled by TRNSYS model Type 651, and cooling towers are modeled by TRNSYS model Type 162. These models were well validated by previous studies according to the TRNSYS 18 user manual [22] and additional modeling was not needed. The only equipment that was modeled by non-TRNSYS models were the pumps.

The pump model computes the pump flow rate based on the speed of the pump and a model of the pressure difference of the pipelines. The pressure difference of the pipeline is estimated by Equation (7) which is a variation from the commonly used fan affinity law [14].

$$\Delta P_{pipe} = \Delta P_{des,pump} \left(\frac{\dot{m}_{pump,tot}}{\dot{m}_{des,pump} \max\left(\left(N_{op,ch} + N_{op,hx}\right)/_{2}, 0.5 \right)} \right)^2 \tag{6}$$

where ΔP is the pressure difference and $\dot{m}_{pump,tot}$ is the total flow rate due to the operation of all operating pumps in its water circuit.

Equation (7) estimates the pressure difference across the equipment in the cooling water circuit or the chilled water circuit based on the number of operating chillers and pumps. It contains two unknowns – the pressure difference across the circuit and the total flow rate of the pumps in a circuit. To solve for the unknowns, one more equation is needed. The equation is obtained by the relationship between pump speed, pump pressure difference and pump flow rate as shown in Equation (8) which was validated in [23].

$$\Delta P_{pump} = c_{pump,0} f_{pump}^2 + c_{pump,1} f_{pump} \dot{m}_{pump}^2 \tag{7}$$

where $c_{pump,0}$ and $c_{pump,1}$ are parameters of the pump model, f_{pump} is the speed of the pump and ΔP_{pump} is the pressure difference across the pumps.

At steady state operation, the pressure differences of the pump and pipelines in a circuit should be equal. Thus, the pressure difference and the flow rate of the pump can be solved after getting the speed of the pump from the control algorithm.

In addition to the pump model, because the study consists of cases with ambient temperature below freezing, an additional electricity heater model was introduced to the cooling tower models to simulate the operation of the heaters to cooling towers that were off under freezing conditions.

Similar to Equation (8), all equipment models contain some empirical parameters that represent the operation characteristics of the equipment. In this study, they are estimated based on regression and the manufacturers' specifications of the equipment in the real data center cooling system in Table 1.

These equipment models are solved according to the simulation procedure in in TRNSYS to estimate the performance of the data center cooling system under a specific condition and operation mode as shown in Figure 10.

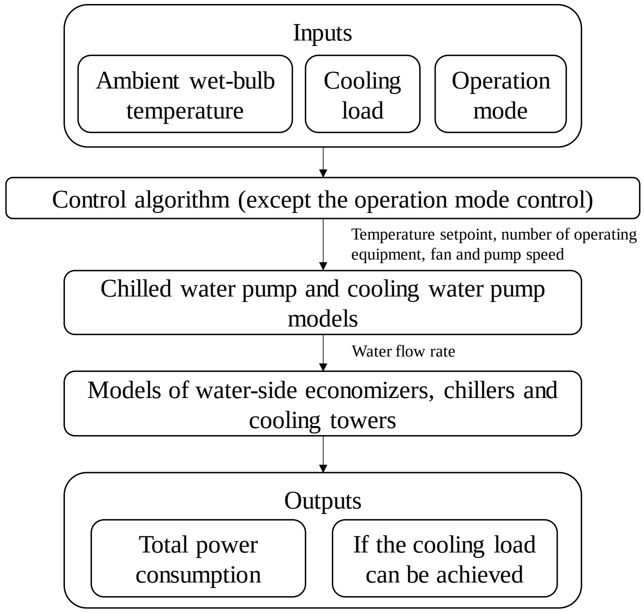

Figure 10 Flowchart to simulate the operation of a data center cooling system in TRNSYS under a specific condition and an operation mode

The operation mode of the data center cooling system is determined by following the procedure in Figure 9. This repeats the simulation in Figure 10 in all three operation modes under the same cooling load and ambient wet-bulb temperature and selects the feasible mode that yields the lowest overall power consumption.

4.4 Operating conditions

To compare the performance of the designs under different weather conditions, the simulation case study is conducted with ambient wet-bulb temperature ranging from 5 °C to 30 °C at 1 K interval and cooling load ranging from 2000 kW and 16000 kW at 500 kW intervals.

To examine the performance of the designs in more realistic situation, the simulation case study is also performed with typical meteorological year (TMY) weather files [26] under different climate zones in Asia as shown in Table 5.

Table 5 Selected climate zones and cities in Asia

Climate zone	Description	Representative city	Climate zone	Description	Representative city
0A	Extremely hot and wet	Bangkok, Thailand	4B	Mixed and dry	Turpan, China
0B	Extremely hot and dry	Abu Dhabi, United Arab Emirates	5A	Cool and wet	Sapporo, Japan

1A	Very hot and wet	Hanoi, Vietnam	5B	Cool and dry	Hami, China
1B	Very hot and dry	Kuwait International Airport, Kuwait	6A	Cold and wet	Changchun, China
2A	Hot and wet	Guangzhou, China	6B	Cold and	Hohhot, China
3A	Warm and wet	Wuhan, China	7	Very cold	Semipalatinsk, Kazakhstan
3B	Warm and dry	Tehran, Iran	8	Subarctic/arctic	Chita, Russia
4A	Mixed and wet	Ulsan, South Korea			

The climate zone coding and description follow that in ASHRAE Standard 169-2013 [27], and the representative cities are chosen from the standard in the Asian region. The simulations are conducted with the hourly ambient temperature and humidity in the TMY file under four cooling loads: 4,000 kW, 8,000 kW, 12,000 kW and 16,000 kW separately to analyze the operation of the data center cooling systems with different designs under various climatic conditions.

5. Results and Discussion

The results of the simulation case study are analyzed in three aspects: the optimal operation modes under different weather, the energy efficiency of the designs, and their operation under different climate zones.

5.1 Optimal operation modes

The optimal operation modes of the system under the Baseline Design and the alternative designs are shown in Figure 11.

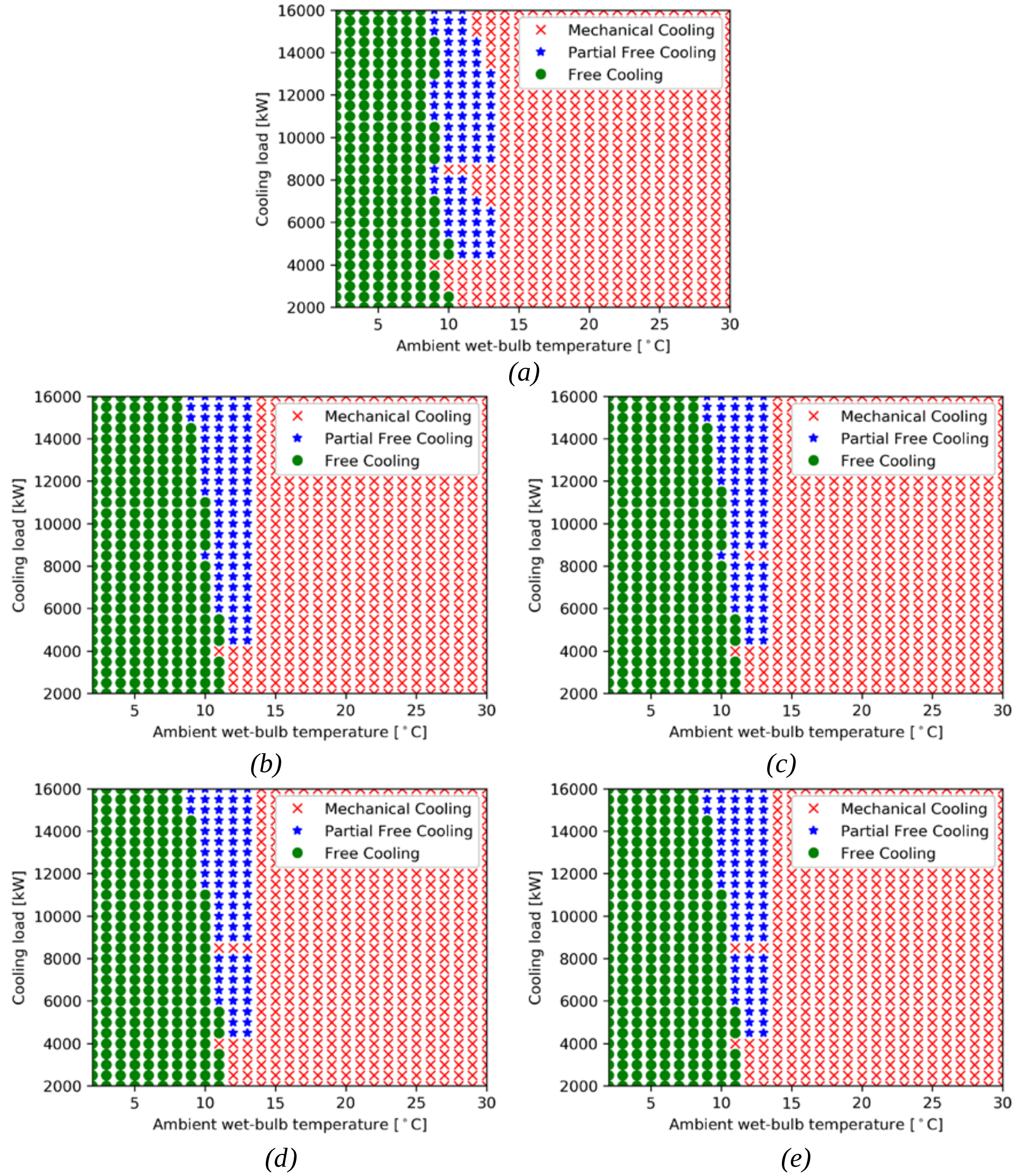

Figure 11 Operation modes of the system in the (a) Baseline Design, (b) Alternative Design 1, (c) Alternative Design 2, (d) Alternative Design 3 and (e) Alternative Design 4

Figure 11 shows that both ambient wet-bulb temperature and cooling load are key factors that affect the operation modes of the system in different designs. As the ambient wet-blub temperature increases, the system operation transitions from free cooling mode to partial free cooling mode and from partial free cooling mode to mechanical cooling mode. Since the chiller plant water supply temperature is 13 °C, the system can only satisfy the cooling load by mechanical cooling when the ambient wet-bulb temperature is above 13 °C. The higher the cooling load, the lower the maximum ambient wet-bulb temperature that allow free cooling operation. At cooling load 4200 kW, the maximum ambient wet-bulb temperature that allows free cooling is 11 °C. When the cooling load increases to 16000 kW, the temperature drops to 8 °C.

The most significant difference between the operation modes of the system in different designs can be found in the number of scenarios using free cooling mode in the Baseline Design case. The number of free cooling mode operations in the Baseline Design is much fewer than that in other alternative designs. The number of partial free cooling mode operations in the Baseline Design is also fewer than that in the other designs. The number and distribution of free cooling mode and partial free cooling mode in the other designs are similar to each other. This shows that the distribution headers around the cooling towers and the associated control algorithm are the main influential factors that increase the cooling capacity of the free cooling and the partial free cooling mode and hence affect their applicability under different operating modes.

5.2 Energy Efficiency of System under Various Designs

To examine which design yields the highest energy efficiency of the systems under various ambient wet-bulb temperature and cooling load, the percentage of power consumption reduction of each alternative design relative to Baseline Design is compared in Table 5 and Figure 12.

Table 6 Average percentages of power consumption reduction of different alternative designs relative to the Baseline Design

Design	**Percentages**
Alternative Design 1	2.79%
Alternative Design 2	5.18%
Alternative Design 3	5.78%
Alternative Design 4	6.14%

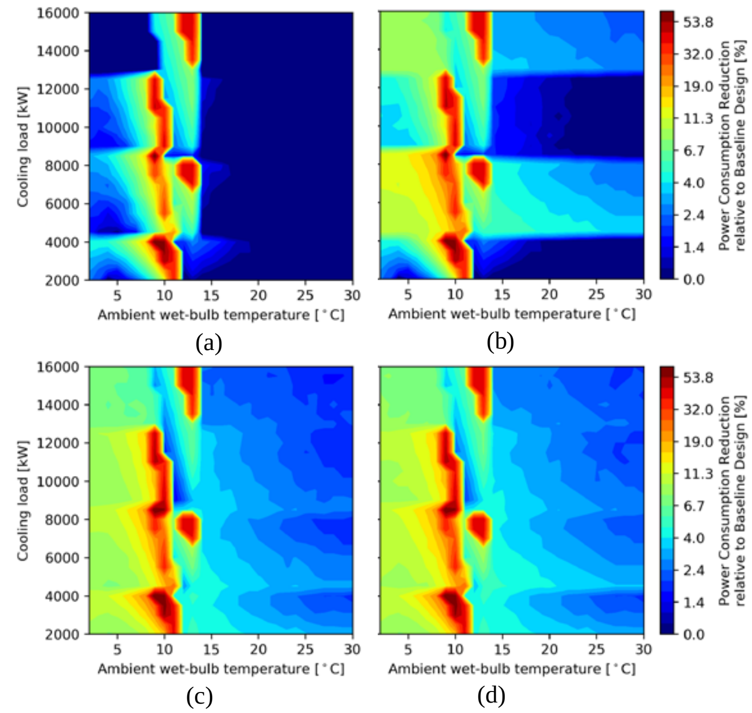

Figure 12 Percentage of power consumption reduction relative to the Baseline Design under various operating condition by (a) Alternative Design 1, (b) Alternative Design 2, (c) Alternative Design 3 and (d) Alternative Design 4

Table 5 shows that the system under all alternative designs use less electricity than the Baseline Design, and Figure 12 shows that the power consumption reduction mainly occurs when ambient wet-bulb temperature is between 9 °C and 13 °C. The maximum percentage of power consumption reduction in this range of wet-bulb temperature can reach 64% which is much larger than the percentages in other ranges of temperature. A comparison between Figure 11 and Figure 12 shows that the region with the largest power consumption reduction in Figure 12 coincides with the leftmost boundary of the mechanical cooling region in Figure 11(a). Under these operating conditions, while the system in the Baseline Design requires mechanical cooling, all alternative designs permit the system to use either partial free cooling operation or free cooling operation to support the cooling operation. The system under alternative designs can operate without chillers under these conditions, and their power consumption becomes much lower than that of the Baseline Design. Hence the distribution headers around the cooling tower and the control algorithm to increase the number of operating cooling towers can increase the energy efficiency of the data center cooling system using water-side economizers significantly.

While Figure 12(a) does not show very different operation between the Baseline Design and the Alternative Design 1 other than the ambient wet-bulb temperature range between 9 °C and 13 °C, the other designs show significant power consumption reduction at other ambient wet-bulb temperature when the cooling load is above 4200 kW. In these designs, when the cooling load is higher than 4200 kW, the system runs cooling water pumps with lower flow capacity than that of the Baseline Design and the Alternative Design 1. The cooling water pump in systems under Alternative Designs 2 to 4 consume less electricity than that of the Baseline Design and the Alternative Design 1. Hence Alternative Designs 2, 3 and 4 manage to operate with lower power consumption at other ambient wet-bulb temperature when the cooling load is above 4200 kW.

Below 4200 kW, only Alternative Designs 3 and 4 can operate with significantly lower power consumption than the Baseline Design. This is because they use smaller cooling water pumps to support the system cooling operation than systems under other designs. Hence Alternative Designs 3 and 4 can achieve better energy efficiency in general than other designs. Similar energy saving phenomenon can be found when the ambient wet-blub temperature is higher than 14 °C and the cooling load is between 8400 kW and 11200 kW.

To further compare the energy efficiency of Alternative Designs 3 and 4, the coefficient of system performance (COSP) of various designs under various operating conditions are calculated by Equation (9).

$$\text{COSP} = \frac{Q}{W_{system}} \quad (8)$$

where Q is the cooling load in kilowatts and W_{system} is the estimated power consumption of the data center cooling system, including pump power consumption, chiller power consumption, etc., in kilowatts

The study can compare the performance of Alternative Designs 3 and 4 by comparing the average COSPs of the systems under all designs and simulated operating conditions in Table 7.

Table 7 Average COSP of different designs under different operating conditions

Designs	**All operating conditions**	**Cooling load above 12600 kW**	**Cooling load between 8400 kW and 12600 kW**	**Cooling load between 8400 kW and 12600 kW**	**Cooling load below 4200 kW**

Baseline Design	7.701	8.087	7.855	7.504	7.123
Alternative Design 1	8.054	8.304	8.232	7.881	7.608
Alternative Design 2	8.340	8.726	8.393	8.353	7.608
Alternative Design 3	8.405	8.607	8.611	8.230	7.986
Alternative Design 4	8.449	8.664	8.655	8.292	7.986

Table 7 shows that the Alternative Design 4 is more efficient than Alternative Design 3 and yields higher COSP on average. While their COSPs are the same at cooling load below 4200 kW, the COSP of Alternative Design 4 is higher when the cooling load is above 4200 kW. At higher cooling load, Alternative Design 4 uses at least 1 large cooling water pump and uses fewer cooling water pumps than Alternative Design 3. The use of both large and small constant-speed pumps in Alternative Design 4 improves the energy efficiency of the system under both low-load and high-load conditions.

5.3 Energy Efficiency of System under Various Climate Zones

To examine the performance of a data center cooling system in realistic situations, the energy efficiency of the systems simulated under different climate zones according to Table 5 is calculated using Equation (9).

$$\text{Average COSP} = \frac{\sum Q\,(t_i)}{\sum W_{system}(t_i)} \tag{9}$$

where t_i is the i^{th} simulation time stamp in a simulation result

The results are summarized in Figure 13.

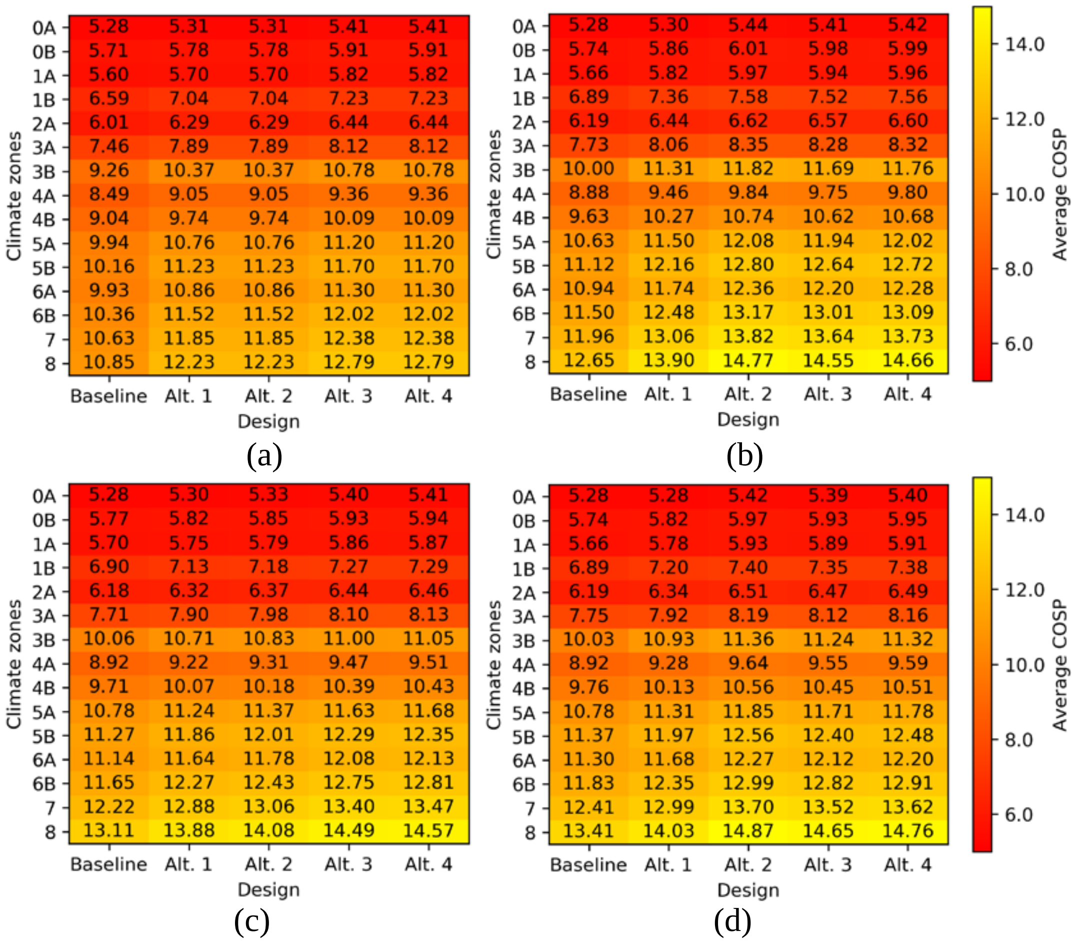

Figure 13 Average COSP of systems in different climate zones with cooling load at (a) 4000 kW, (b) 8000 kW, (c) 12000 kW and (d) 16000 kW

Figure 13 shows consistent results with the previous analyses. A system can operate with higher average COSP under climates that are colder and drier. One anomaly is that the average COSP in climate zone 3B is as high as that in climate zones 5A and 5B. The reason can be found in the operation time of the mechanical cooling mode in different climate zones under different load in Figure 14.

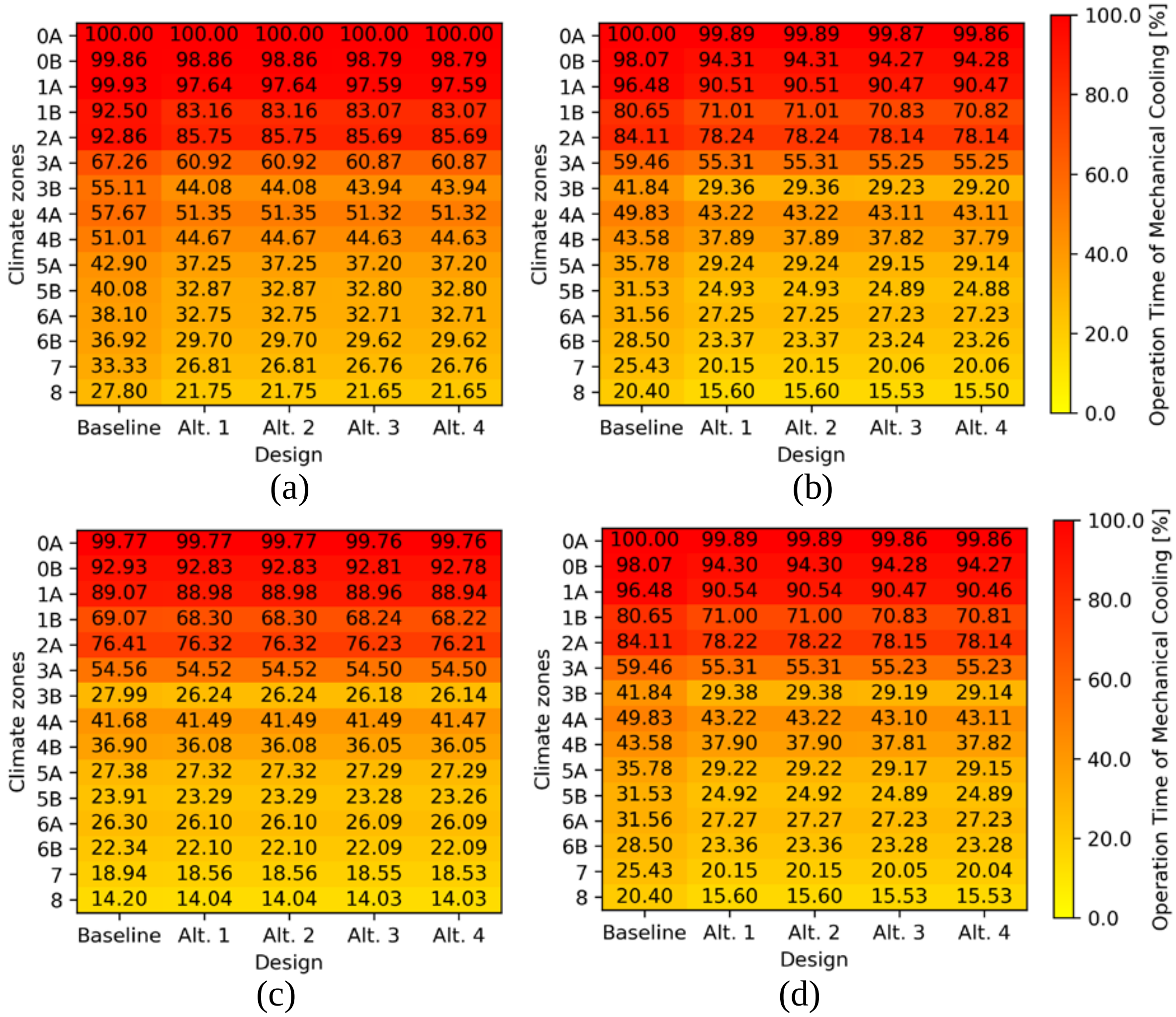

Figure 14 Operation time of different designs in different climate zones with cooling load at (a) 4000 kW, (b) 8000kW, (c) 12000 kW and (d) 16000 kW

Figure 14 shows that the temperature and humidity in climate zone 3B allow the system to run in mechanical cooling mode for around 30% of a year only. The time the system spent in mechanical cooling mode in climate zone 3B is similar that of ones in climate zones 5A and 5B. This explains why the system can consume less energy in climate zone 3B than that in climate zones 5A and 5B.

To examine which design should be used to replace the Baseline Design under different climate zones, the reduction of annual electricity consumption due to the replacement of the Baseline Design by an alternative design is plotted in Figure 15.

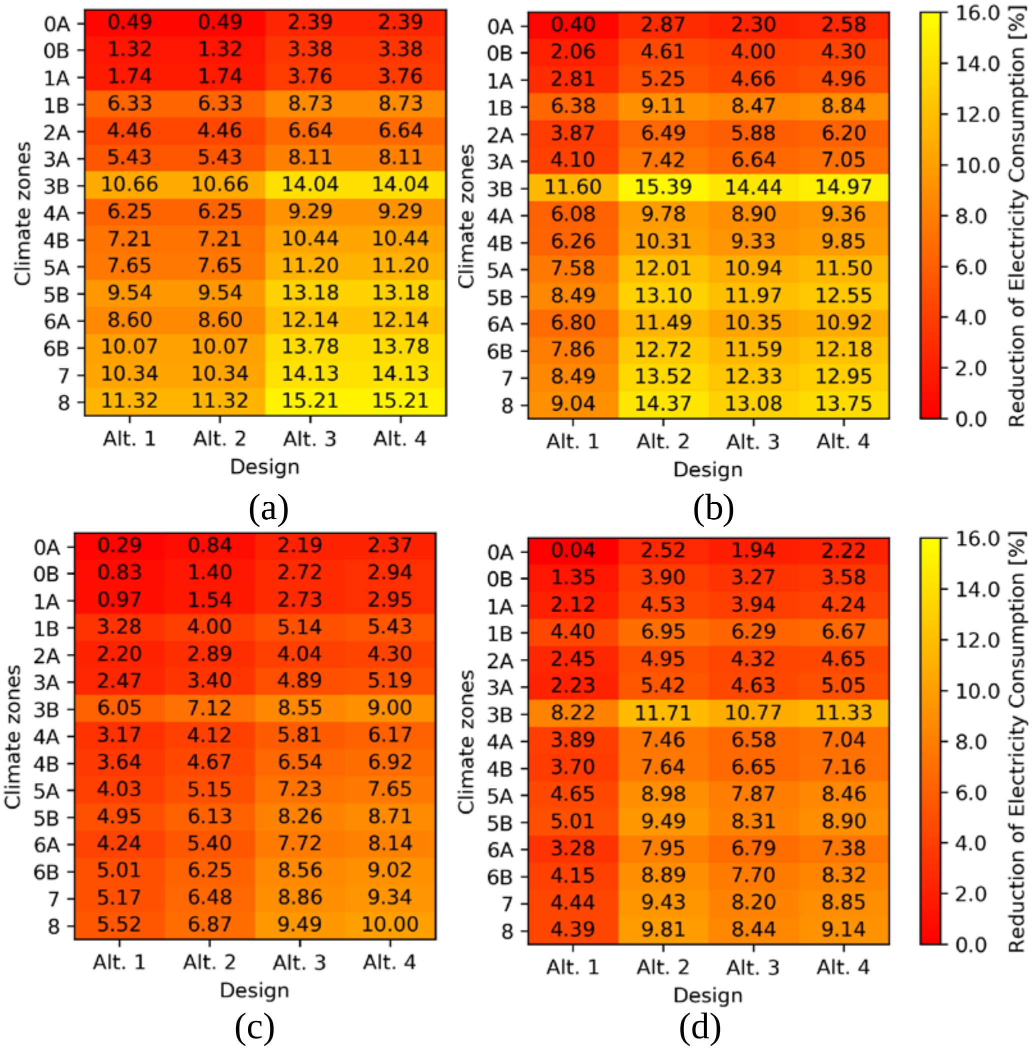

Figure 15 Reduction of annual electricity consumption from the Baseline Design with cooling load at (a) 4000 kW, (b) 8000kW, (c) 12000 kW and (d) 16000 kW

Figure 15 shows that Alternative Design 4 can lead to better energy efficiency improvement than other designs in most situations. It can reduce system energy use by 2.6% to 15%. Although Alternative Design 2 can reduce the data center energy consumption a little more than Alternative Design 4 in some situation, its energy saving can at most leads that of Alternative Design 4 by 0.67% only. In cases which Alternative Design 2 underperforms that of Alternative Design 4, the energy saving of Alternative Design 2 can be lower than that of Alternative Design 4 by 3.89%. Hence Alternative Design 4 is the best design.

6. Conclusions

This study evaluates different piping and pump designs and optimal control algorithms to suggest an optimized design of free cooling systems in data centers. Using a steady-state model of a realistic data center cooling system, the study compares the energy efficiency of five different data center cooling system designs at different ambient wet-bulb temperature and cooling load. The results show that an optimal design of a free cooling system should contain the following three features:

1) Distribution headers around cooling towers and a control algorithm to operate more cooling towers than necessary;

2) Distribution headers around pumps and a control algorithm to minimize the number of operating pumps;

3) A mix of large and small pumps and an appropriate pump sequencing control algorithm.

Based on the simulations under different operating conditions and climate zones, the study shows that these designs can reduce the energy consumption of a data center cooling system with water-side economizers by 3 to 15% annually and as much as 60% under some specific conditions. This verifies that the designs can improve the energy efficiency of data centers significantly.

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Nomenclature

Roman	
c	Empirical parameter [unit varies]
COSP	Coefficient of system performance

$\dot{m}$	Mass flow rate [kg/h]
N	Number of equipment
P	Pressure [kPa]
Q	Cooling load [kW]
T	Temperature [°C]
W	Power consumption [kW]
Greek	
Δ	Difference
Subscript	
ch	Chiller
chp	Chilled water pump
chw	Chilled water
ct	Cooling tower
des	Design
hx	Water-side economizer
op	Operating
pipe	Pipeline
pump	Pump
req	Required
setpt	Setpoint
system	Data center cooling system
tot	Total

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