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Reliability and availability analysis of a hybrid cooling system with water-side economizer in data center

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ABSTRACT

The cost of data center downtime has increased significantly recently and it is critical for any data center to minimize the unplanned downtime. A reliable cooling system is of great importance to ensure the thermal environment and achieve this goal. The reliability and availability analysis (RAA) is a scientific way to quantify the risk and determine the potential solutions for a system design and operation. Hybrid cooling system with water-side economizer as a promising energy saving method in data center has complicated configuration and multi operation modes. Thus, it is very necessary to conduct the RAA on this novel system and understand it. In this study, the Markov model combined with reliability block diagram method, which can drastically reduce the computation dimension, was developed to evaluate the reliability and operational availability (OA). Functional Availability (FA) was presented as a new measure by integrating OA with specific function criteria such as room temperature. Additionally, we proposed *a maximum allowable downtime (MADT)* to quantify how long a repair time is acceptable in different scenarios. The detailed method, evaluation procedure and results of a hybrid cooling system were presented.

1. Introduction

In recent years, due to the progress and development of Information and Communications Technology (ICT), computational data storage and process and the backbone facility-data center-are indispensable to nearly all businesses. In general, data center facilities could have heat densities 100 times more than that of a typical comparably sized office space and consume 35–50 times the amount of energy that an office will use [1,2]. Recent energy statistics indicate that the data center industry is responsible for 1.3% of the total electricity consumption in the world [3] and this percentage is even much higher (1.8%) in US [4]. Consequently, harnessing the energy consumption for the data center is a huge challenge. The data center cooling system runs 24/7/365, and it accounts for 30–50% of the overall energy consumed of data centers [3,5]. Among the many energy saving solutions, water-side economizer arouses significant attentions for energy conservation measures since it allows for free cooling (without the use of chiller) when low temperature outside water is available [6,7]. However, the water-side economizer is intermittently available and it needs to couple with a traditional chiller cooling system. This hybrid cooling system has more complex system configuration and multi operation modes. Reliability and availability (RA) evaluation is an important, often indispensable, step in designing and analyzing (critical) redundancy and maintenance policies.

The primary task of a cooling system is to maintain data centers at an acceptable temperature for servers instead of staffs. The thermal environment of data centers must be rigorously controlled according to ASHRAE's “Thermal Guidelines for Data Processing Environments” at all time when servers are in operation [8]. The reason is that the probability of failure of the ICT equipment increases greatly when the working conditions are out of manufacturer's specified temperature range. The 2016 report of Ponemon Institute [9] analyzed the sample of 63 data centers by the primary root cause of unplanned downtime. Therein the water, heat, CRAC failure accounts for 11% and the weather related is 10%. According to the report [9], the average cost of data center unplanned downtime across industries was approximately $5600 per minute in 2010 and it increased to nearly $9000 per minute in 2016. Thus, we should accurately evaluate the RA properties of data center cooling system, which helps to improve the RA and minimize data center downtime by taking proper changes and action.

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Reliability is defined as the probability that a system component produces correct outputs up to some given time t [10], which can be characterized in terms of mean time between failures (MTBF) (i.e. reliability = $exp(-t/MTBF)$. Availability is a measure of the probability that a system/component is operational at a given time, which is typically given as a percentage of the time a system/component is expected to be available, e.g., 99.99 percent ("four nines"). Reliability and availability analysis (RAA) is an efficient way to understand how to avoid/reduce losses caused by the failure of components/systems; it has been successfully used in industrial manufacture power system and computer science [11,12]. While the terminology is not new, only a limited amount of completed research was found in the area of RAA for cooling system. Peyton et al. [13] presented the survey of RA information of single component for 204 items, including power distribution, power generation, and Heating, Ventilation, Air-conditioning (HVAC) components for commercial, industrial, and utility installations. Myrefelt [14,15] applied the reliability theory to building HVAC facilities and defined the concepts of OA and FA based on standard reliability equations. In Ref. [16], the reliability assessment of cooling system equipment with Markov model was applied in commercial building energy system optimization design practice. In Ref. [10], the Markov model was expressed as a state-space form to analyze the RA of the redundant building cooling, heating and power system. In the specific area of data center, few studies focused on the power system. Shrestha et al. [17] studied the reliability of Direct Current (DC) distribution in data centers, including the analysis of different level of redundancy (e.g. N, N + 1, N + 2) in the Uninterruptible Power System (UPS) for both Alternating Current (AC) and DC systems. In Ref. [18], the relationship between the reliability of a data-center air-conditioning system and the air-conditioning power supply configurations was reported. In Ref. [19], Dai et al. identified the reliability of parts of ICT equipment under select existing or emerging energy efficient cooling methods (i.e. air or liquid cooling).

Besides the limited studies, we also found the majority of the research only deal with the general availability. The availability refers to the availability of the system itself (i.e. the parameter focuses on the operation state of the system regardless of the target control variables, so-called operational availability (OA)); that is, a system is judged as "faulty" when the system fails to operate normally. To assess the reliability and OA for repairable multistate system (the system cannot formulate an "all or nothing"), random processes methods, such as Markov method, are generally suggested [20]. However, this straightforward stochastic process method is very difficult for application in complex data center cooling system. Especially, the hybrid cooling systems with water-side economizer that we study has more complex system configuration and multi operation modes. The correct definitions of all states and transition between states are extremely challenging for systems like this [21]. Thus, this study introduced the reliability block diagram (RBD) method to decompose the system with multilayer structure (e.g. components, subsystem, cooling sink and cooling mode) and solve the "dimension damnation".

The OA is determined by the system configuration, which is enough for availability analysis in the area of power distribution and ICT parts. However, from the view of function of cooling system in data centers, it is more reasonable to use the ICT equipment's working environment to judge the availability of data center cooling system. Even if the system configuration is fixed, the OA of cooling system in data center will vary with the Data Center Class, internal heat density, start-up characteristics of cooling system, repair time of system failure, etc. Thus, we further proposed functional availability (FA) as a new measure to evaluate the availability for data center cooling system. The FA is an extended product of the OA which also needs to meet function criteria such as servers' ambient temperature. For example, in order to minimize the data center downtime, the server's ambient temperature should be in the intended range over the lifetime. When the system is not in the intended operational state, estimates of the allowable repair time is necessary for developing repair instructions. Thus, this study defined a new metric based on FA, the *maximum allowable downtime* (*MADT*), to quantify whether a repair time is acceptable or not.

Motivated by the above findings, this paper proposed the RAA method for hybrid cooling systems with water-side economizer in data center. A real data center hybrid cooling system was used as the prototype system. The reliability and OA analysis was carried out for different operation modes and component configurations. FA calculation model was developed by marrying OA with specific function criteria such as room temperature. And the MADT was calculated for different heat densities, Data Center Class and cooling systems with different start-up time. The contribution of this research has four folds: 1. First of its kind in applying a RAA method to hybrid cooling system; 2. Coupling Markov model and diagram method to reduce the computational dimension and solve the dimension damnation; 3. Proposing FA for data center where the maintenance of the control variable matters; and 4. Estimating MADT in event of operational failure to provide repair instructions. Successful application of this research helps to improve system's RA in reality in both design and operation stage.

The rest of the paper is organized as follows. Section 2 presents methods of RAA for cooling system in data center. Section 3 introduces its application on a hybrid cooling system in practical data center to illustrate the procedure. Redundant setting analysis using OA and MADT analysis obtained from FA for different scenarios, were investigated and discussed in Section 4. Conclusions and future works are given in Section 5.

2. Methods

Fig. 1 shows the basic idea of the proposed RAA estimation process for cooling system in data center, which consists of four steps: *system decomposition, state probability estimation, reliability and operational*

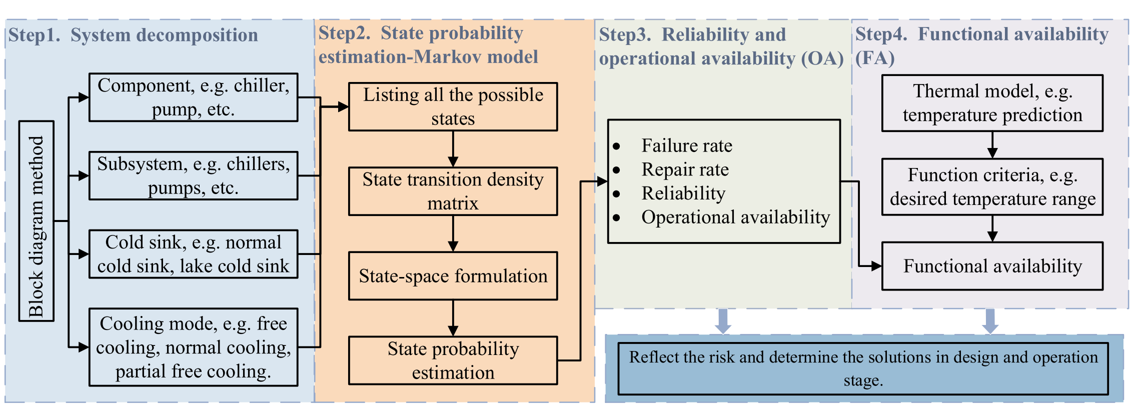

Fig. 1. Process of RAA for cooling system in data center.

availability (OA), functional availability (FA). Based on this method, we can evaluate the risk and find effective solutions to improve the RA and minimize the data center downtime, such as the redundant settings, selections of start-up time and repair time of cooling system, room temperature set-point for different Data Center Class, etc.

2.1. System decomposition and integration

The complex hybrid cooling system has many kinds of equipment; some of them even have multiple units. As mentioned above, it is a difficult assessment to correctly define all states and transition density matrix for Markov model in component level. A reliability block diagram (RBD) is a method to show how the failure or success of component contributes to the failure or success of a system [21]. It is used to illustrate the interdependencies among all components of a system by concise visual shorthand. To develop the RBD, the entire cooling system can be naturally decomposed and drawn into a series of blocks. Each block of the RBD represents one element of the function contained in the system. All blocks are connected in parallel, series or standby configurations. For data center cooling system, several blocks can merge into one block and a multilayer structure is developed describing the functional elements necessary to provide cooling for data center. The number of blocks per layer can be small enough for easy definition of all states and transition density matrix. Each block is populated with both failure rate and repair rate to characterize the RA properties.

2.2. State probability estimation

The failure rate of each component of HVAC system follows the bathtub curve [14,22]. It is high in the beginning and ending while keep a constant under the steady period. Since this study focused only on the steady state period, the constant failure rate λ and repair rate μ were used for RAA. The aim of using Markov model was to estimate the probabilities of each state of the system at a specific period, which can be decomposed into four steps, including:

- Listing all the possible states of the analytic target (e.g. subsystem, cold sink and cooling mode), including operating state and failed state;
- Determining the state transition density matrix, which is determined by the failure rate and the repair rate of component or subsystem in the cooling system;
- Developing the state-space formulation based on previous two steps.
- Calculating the probabilities of each state.

A HVAC system consists of n components or subsystems, assuming each component or subsystem only has two states, on/off. Therefore, the entire system totally has 2^n states and each state is set with a unique serial number. In this study, we assumed that state 1 represents the best performance and the performance deteriorates as the serial number of the state increases. In other words, state k ($1 \le k \le 2^n$-1) has better performance than state $k+1$.

The prescribed system may transfer from one state to another during a given period when the component fails or is under repair. The differential equations for finding the instantaneous state probabilities $p_i(t)$, $i = 1,..,2^n$ for the homogeneous Markov process [20] can be written as follows:

$$\frac{dp_i(t)}{dt} = \left[\sum_{\substack{j=1 \\ j\neq i}}^{2^n} p_j(t)a_{ji}\right] - p_i(t)\sum_{\substack{j=1 \\ j\neq i}}^{2^n} a_{ij} \tag{1}$$

In which, i,j *is* the serial number of the state. $p_j(t)$ is the probability of state j, $j = 1, \ldots, 2^n$. a_{ij} is the transition intensity from state i to state j. And a_{ji} is the transition intensity from state j to state i. In this study, all transitions are caused by the components' failures and repairs, which can be expressed by the components' failure rates and repair rates. The transition intensity can be calculated with the following equation:

$$\begin{cases} a_{ij} = \lambda_{ij}, \quad i < j \\ \quad \Leftrightarrow \ \textit{Transition from state } i \textit{ to state } j \textit{ is caused by the} \\ \quad \textit{components' failures.} \\ a_{ij} = \mu_{ij}, \quad i > j \\ \quad \Leftrightarrow \ \textit{Transition from state } i \textit{ to state } j \textit{ is caused by the} \\ \quad \textit{components' repairs.} \end{cases} \tag{2}$$

According to the above equation, it can also be formulated using the state-space representation as follows:

$$\frac{d}{dt}P(t) = P(t)D \tag{3}$$

Where the state probability matrix is

$$\begin{cases} P(t) = [p_1(t), p_2(t), \ldots, p_{2^n}(t)] \\ p_1(t) + p_2(t) + \cdots + p_{2^n}(t) = 1 \end{cases} \tag{3a}$$

And the density matrix is

$$D = \begin{bmatrix} d_{11} & d_{12} & \cdots & d_{12^n} \\ d_{21} & d_{22} & \cdots & d_{22^n} \\ \vdots & \vdots & \ddots & \vdots \\ d_{2^n1} & d_{2^n2} & \cdots & d_{2^n2^n} \end{bmatrix} \tag{3b}$$

$$\begin{cases} d_{ij} = a_{ij}, \quad i \neq j \\ d_{ii} = -\sum_{i\neq j} a_{ij} \end{cases} \tag{3c}$$

We assume that the initial states of all components are normal operating, i.e. the initial probabilities $p_1(0) = 1$, $p_2(0) = p_3(0) \ldots = p_{2^n}(0) = 0$. Therefore, the instantaneous state probabilities can be obtained by solving Eq. (3). And the steady state probabilities can be expressed by the following state equations:

$$\begin{cases} \mathrm{PD}=0 \\ p_1 + p_2 + \cdots + p_{2^n} = 1 \end{cases} \tag{3d}$$

2.3. The reliability and operational availability (OA)

The OA is calculated as the probability that the system will be in the intended operational state. According to the RBD and the operation states table of the analytic target, the OA is the sum of the probabilities of all feasible operational states. The probabilities of all system states can be calculated with step 2. Thus, the OA can be obtained. The detailed derivation for specific example can be found in Section 3.2.

Identically, according to the definition, the OA also can be expressed as a function of the failure rate (λ_{sys}) and repair rate (μ_{sys}) of the system:

$$A_{o,sys}(\infty) = \frac{1}{\lambda_{sys}/\mu_{sys} + 1} \tag{4}$$

where

$$\lambda_{sys} = 1/MTTF_{sys}, \quad \mu_{sys} = 1/MTTR_{sys} \tag{4a}$$

where $MTTF_{sys}$, $MTTR_{sys}$ are the mean time to failure and mean time to repair of the system, respectively.

Then the reliability and OA of a system with the time can be written as:

$$R_{sys}(t) = e^{-\lambda_{sys}t} \tag{5}$$

Base on above mentioned two expressions for the OA, the failure rate and repair rate of a system can be calculated. The detailed

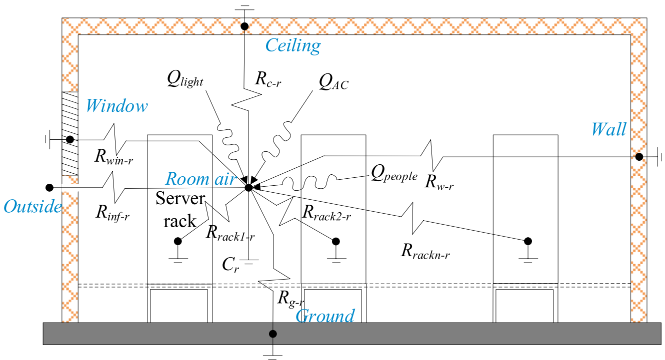

Fig. 2. Schematic diagram of the thermal network in data center zone.

derivation of these RA properties for redundant system, series system as well as parallel system can be found in Section 3.2. Then, the RA properties of the whole system can be obtained.

2.4. The functional availability (FA)

The operational condition variable in this study is the ambient temperature of servers, i.e. the room temperature of data center. Therefore, to analyze the FA of cooling system in data center, the future evolution of room temperature needs accurate calculation based upon the servers' working condition. A schematic diagram of the thermal network in data center zone considered in the present study is shown in Fig. 2. The data center zone temperature is with the boundary condition for wall, ceiling and ground surfaces. The radiation heat exchange between internal surfaces is considered in the model but it is not shown in the figure for simplicity. The room temperature of data center can be calculated as follows [2]:

$$C_r \frac{dT_r}{dt} = \sum_j \frac{T_j - T_r}{R_{j-r}} + \sum_k Q_k \tag{6}$$

where, C_r is the heat capacity of room air. T_r, T_j are the room air temperature and node j temperature, respectively. $R_{j\text{-}r}$ is the heat transfer resistance between node j and room node. Q_k is the internal heat gain, including air conditioning, lighting, and people.

In the process of data center load calculation, the indoor and outdoor temperature as well as internal heat gain of each building should be specified before the sizing and selection of HVAC equipment capacities. The capacity of each cooling system equipment shall be able to supply adequate cool energy for the maximum server load in the hottest condition (among 20 years in history) [23]. Moreover, a general rule is that a cooling system rating must be 1.3 times the anticipated information technology equipment load rating plus any capacity added for redundancy [24]. It is reasonable to assume that the data center temperature is always within the manufacturer's specified temperature range when the cold supply is functionally normal, i.e. the FA is satisfied under normal operation of cooling system. Thus, we only examined in detail whether a room temperature is guaranteed for some specific period (i.e. abnormal condition), such as, a failure of equipment or power supply system resulting in the cold supply failure, or during cooling mode switching moment when it causes a short shutdown to cooling system, etc.

The FA depends strongly on the function criteria [14]. In this study, the FA connected to the cooling system for ICT equipment is related to the room temperature. The overall FA of the data centers cooling system is mainly determined by the following factors: the OA, Data center Class, heat density, heat transfer characteristics of room temperature, start-up time of cooling system and repair time of cooling system failure, etc. Then the FA can be calculated as:

$$A_{f,sys}(\infty) = A_{o,sys}(\infty) \times (1 - p_{us}) + (1 - A_{o,sys}(\infty)) \times p_t \tag{7}$$

where $A_{o,sys}(\infty)$ is the OA of cooling system; p_{us} is the probability of room temperature out of intended range when the system is under operation state. And p_t is the probability of intended value of room temperature when the cooling system fails. For example, assuming that a cooling system fails once *per hour* and the failure lasts *five minutes*, then the cooling system restarts. The evolution of server's working thermal environment is calculated: in *first two minutes* of the failure period, the room temperature is still within the manufacturer's intended temperature range due to the thermal inertia; while it is over the permissible temperature in *other three minutes*; then during the operation state, the room temperature continues to exceed the permissible temperature for a period of time (e.g. 4 mins) after the system restarts due to the delay characteristics of the cooling system. Thus, the OA can be calculated as (3600-300)/3600 = 0.99167 and the FA is 0.99167 × (1–240/(3600-300)) + (1–0.99167) × (2/5) = 0.92288, respectively.

3. Application in a hybrid cooling system case

3.1. Brief introduction of the cooling system

The studied data center is located in Dongjiang Lake, Chenzhou city, China, belonging to the hot summer and cold winter zone. The cooling system can utilize the cold lake water to cool the data center due to the low-temperature water and stable water level throughout the year [25]. As shown in Fig. 3, this data center operates two floors currently, including server room, infrastructure room (e.g. power supply room and refrigeration room) and ancillary device room. The design of the cooling system followed the ASHRAE thermal guidelines for data processing environment [8] and the data center design guidelines GB 50174-2017 [23]. In this paper, a backup component with the same capacity (N + 1) was design to meet the Tier 3 standard [26]. The cooling system proposed in this study is one kind of hybrid cooling system, including normal chiller cooling and lake water cooling. The

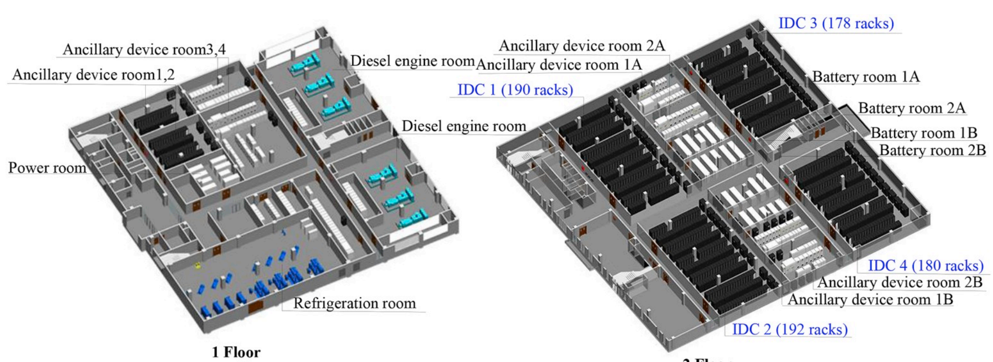

Fig. 3. Layout of data center in Dongjiang Lake.

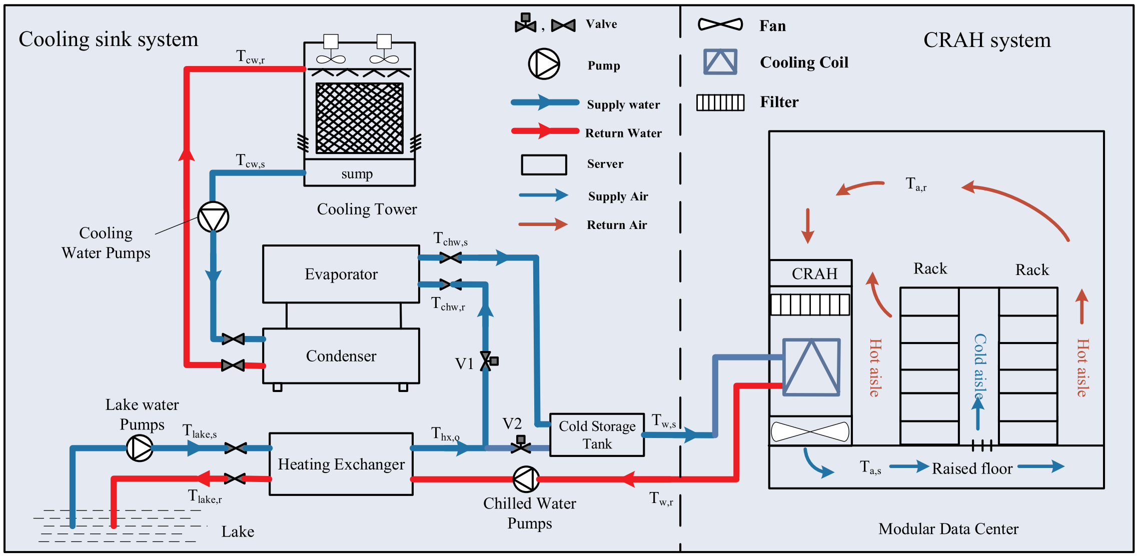

Fig. 4. Schematic diagram of hybrid cooling system with water-side economizer in data center.

CRAH units were designed to cool the ICT equipment.

The schematic diagram of cooling system with water-side economizer in data center is shown in Fig. 4. It mainly consists of plate heat exchangers (e.g. 3 + 1), cooling towers (e.g. 3 + 1), water cooling chillers (e.g. 3 + 1), lake water pumps (e.g. 3 + 1), cooling water pumps (e.g. 3 + 1), chilled water pumps (e.g. 3 + 1) and computer room air handlers (CRAHs) (20 + 1), etc. This hybrid cooling system can operate in three discrete modes in accordance to the lake water temperature: *Free cooling mode*, when the lake water temperature is low enough and can completely satisfy the application cooling load, the lake water sink is used directly to cool data center through the heat exchangers and the chillers are all off; *Partial free cooling mode*, when the lake water sink doesn't completely follow the data center cooling load, chillers as an auxiliary are used to supplement the shortage; *Normal operation mode*, only chillers are used to cool the water circulating to the terminal equipment (CRAHs) during the period with high lake water temperature. In the following Section, the reliability and OA of each subsystem were firstly analyzed and discussed.

3.2. Reliability and OA calculation procedure

In this section, RA properties of this proposed hybrid cooling system were calculated based on Markov model combined with RBD method. As mentioned above, the proposed hybrid cooling system mainly consists of four heat exchangers, four chillers, four cooling towers, four lake water pumps, four cooling water pumps, four chilled water pumps, 20 + 1 CRAHs etc. We assumed that each component only has two states (operating or failed). Then the total operation states of the overall cooling system can be calculated as $2^{(4\times6+20+1)}$. It is very difficult assignment to identify all states and transition density matrix. Thus, the RBD method was used to develop the multilayer structure and the number of blocks per layer can be reduced, as shown in Fig. 5. The RA properties of each level can be evaluated based on Markov model. First, three cases including redundant system, series system and parallel system were discussed and the calculation rules of these system's repair rate and failure rate were obtained. Then, the RA properties of whole system with different cooling operation modes were calculated based on above derived calculation rules.

According to previous survey of RA information for part level [13], the failure rate and repair rate of main components installed in this proposed hybrid cooling system are shown in Table 1. Here for simplicity, the RA properties of connected accessories were integrated into the main components. For example, the failure rate of one chiller component, contains a chiller, control panel, piping, valve, etc.

3.2.1. Procedure for a redundant system

Herein the chiller subsystem was adopted to illustrate the RA properties calculation procedure of a redundant system. This simple subsystem made up of four chillers, three chillers were the basic chillers to meet the cooling demand and another one was installed as a backup to ensure continuous operation when one chiller fails or needs maintenance. In this study, we defined the states based upon the number of failure chillers and each state contained several situations, i.e. different combination of failure chillers. The number of states in the chiller subsystem was reduced from 2^4 (assuming each chiller only has two states, on/off) to 5, as described in Table 2. State$_{ch}$ 1 means that all chillers are under normal operation state; State$_{ch}$ 2 means that one chiller fails and three chillers are under normal operation state, etc. And the state transition grand of the chiller subsystem is shown in Fig. 6. Each state can transfer to the other four states through repairs and failures. Then based on the law of combination and Eqs. (2) and (3), the parameters of the state transitions for a subsystem composed of n same components can be derived as:

$$d_{ij} = \begin{cases} C_{n-1}^{i-1}\cdot C_{n-i}^{j-i}\cdot\lambda, & i<j \\ -d_{i1} - \cdots d_{i(j-1)} - d_{i(j+1)} - \cdots - d_{in}, & i=j \\ C_{n-1}^{i-1}\cdot C_{i-1}^{i-j}\cdot\mu, & i>j \end{cases} \tag{8}$$

Then the transition density matrix of four chillers can be written as:

$$D_{ch} = \begin{bmatrix} -15\lambda_{ch} & 4\lambda_{ch} & 6\lambda_{ch} & 4\lambda_{ch} & \lambda_{ch} \\ 4\mu_{ch} & -28\lambda_{ch}-4\mu_{ch} & 12\lambda_{ch} & 12\lambda_{ch} & 4\lambda_{ch} \\ 6\mu_{ch} & 12\mu_{ch} & -18\mu_{ch}-18\lambda_{ch} & 12\lambda_{ch} & 6\lambda_{ch} \\ 4\mu_{ch} & 12\mu_{ch} & 12\mu_{ch} & -28\mu_{ch}-4\lambda_{ch} & 4\lambda_{ch} \\ \mu_{ch} & 4\mu_{ch} & 6\mu_{ch} & 4\mu_{ch} & -15\mu_{ch} \end{bmatrix} \tag{9}$$

where λ_{ch}, μ_{ch} are the failure rate and repair rate of one chiller, respectively.

The steady state probabilities of the chiller subsystem can be expressed as:

$$[p_1 \quad p_2 \quad p_3 \quad p_4 \quad p_5]D_{ch} = [0 \quad 0 \quad 0 \quad 0 \quad 0] \tag{10}$$

Namely:

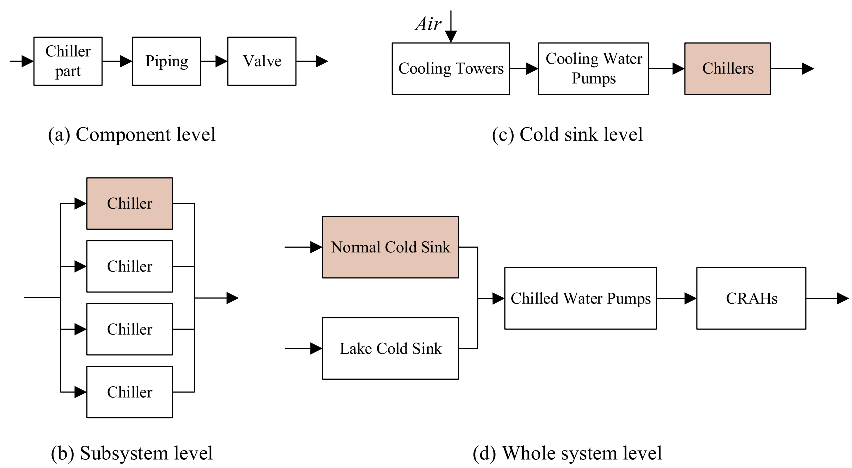

Fig. 5. The reliability block diagram for the hybrid cooling system.

Table 1
The failure rate and repair rate of main components of cooling system [13].

Components	Failure rate		Repair rate	
	Symbol	Value,/hour	Symbol	Value,/hour
Chiller	λ_{ch}	0.000018898	μ_{ch}	0.16117
Cooling tower	λ_{ct}	0.000022285	μ_{ct}	0.026681
Heat exchanger	λ_{hx}	0.000011699	μ_{hx}	0.28380
Water pump	λ_{wp}	0.000012776	μ_{wp}	0.27232
CRAH	λ_{CRAH}	0.000016207	μ_{CRAH}	0.16089

Table 2
The operation states and probability data for chiller subsystem.

	State_{ch} 1	State_{ch} 2	State_{ch} 3	State_{ch} 4	State_{ch} 5
Number of chiller fails	Zero	One	Two	Three	Four
State of subsystem level	1	1	0	0	0
Probability	0.999581	0.000339	0.000054	0.000018	0.000008

* 1 denotes the operation state in whole paper. 0 denotes the failure state in whole paper.

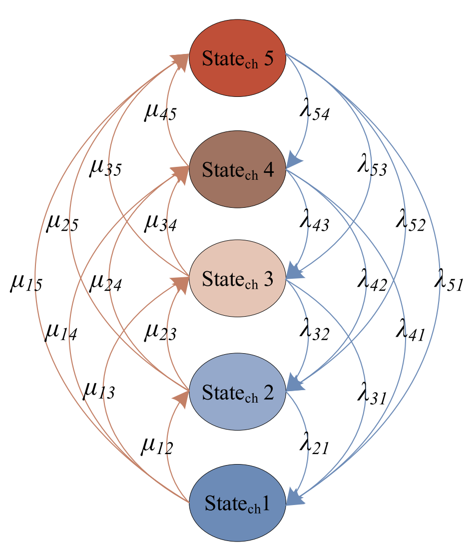

Fig. 6. States diagram of the chiller subsystem and related transitions.

$$\begin{cases} -15\lambda_{ch}p_1 + \mu_{ch}(4p_2 + 6p_3 + 4p_4 + p_5) = 0 \\ \lambda_{ch}(4p_1 - 28p_2) + \mu_{ch}(-4p_2+12p_3 + 12p_4 + 4p_5) = 0 \\ \lambda_{ch}(6p_1 + 12p_2 - 18p_3) + \mu_{ch}(-18p_3 + 12p_4 + 6p_5) = 0 \\ \lambda_{ch}(4p_1 + 12p_2 + 12p_3 - 4p_4) + \mu_{ch}(-28p_4 + 4p_5) = 0 \\ \lambda_{ch}(p_1 + 4p_2 + 6p_3 + 4p_4) - 15\mu_{ch}p_5 = 0 \\ p_1 + p_2 + p_3 + p_4 + p_5 = 1 \end{cases} \tag{11}$$

Then the equation set can be solved and the probabilities of each state were listed in Table 2. Since the chiller subsystem has one redundancy, the normal operation state of the chiller subsystem contains state_{ch} 1 and state_{ch} 2 and its OA is:

$$A_{o,sys,ch} = p_1 + p_2 = 0.999581 + 0.000339 = 0.99992 \tag{12}$$

Where p_1 and p_2 represent the probabilities of state 1 and state 2, respectively.

The reliability of a system with redundant units can be expressed by Ref. [27]:

$$R(t) = \sum_{k=m}^{n} \frac{n!}{k!(n-k)!}(e^{-\lambda t})^k(1 - e^{-\lambda t})^{(n-k)} \tag{13}$$

in which, $R(t)$ is derived using the most general $R(t)$ equation for "m of n Must Be Working" and n is fully energized identical parallel units. So the reliability of a typical chiller subsystem, which contains three basic chillers and one backup chiller, can be written as:

$$R_{sys,ch}(t) = R_{ch}^4 + C_4^1 \cdot R_{ch}^3(1 - R_{ch}^1) = -3e^{-4\lambda_{ch}\cdot t} + 4e^{-3\lambda_{ch}\cdot t} \tag{14}$$

where $R(t)_{ch}$ is the reliability value of one chiller and t represents the time.

The mean time to failure ($MTTF_{sys,ch}$) of the chiller subsystem can be numerically evaluated using Gauss Integration and the system failure rate ($\lambda_{sys,ch}$) is the inverse of the system $MTTF$, which can be calculated by the following equations [27]:

$$MTTF_{sys,ch} = \int_0^{\infty} R_{sys,ch}(t)dt \tag{15}$$

$$\lambda_{sys,ch} = \frac{1}{MTTF_{sys,ch}} = \frac{1}{\int_0^{\infty} R_{sys,ch}(t)dt} \tag{16}$$

Meanwhile, the OA of this chiller subsystem also can be calculated with the failure rate and repair rate by the following equation:

$$A_{o,sys,ch} = \frac{\mu_{sys,ch}}{\mu_{sys,ch} + \lambda_{sys,ch}} \tag{17}$$

So the repair rate of chiller subsystem can be formulated as:

$$\mu_{sys,ch} = \frac{A_{o,sys,ch}\cdot\lambda_{sys,ch}}{1 - A_{sys,ch}} \tag{18}$$

Table 3
The RA properties of each subsystem.

Subsystems	Failure rate		Repair rate		Operational availability
	Symbol	Value,/h	Symbol	Value,/h	
Chillers (3 + 1)	$\lambda_{sys,ch}$	0.00003239726	$\mu_{sys,ch}$	0.40836203368	0.999921
Cooling towers (3 + 1)	$\lambda_{sys,ct}$	0.00003820354	$\mu_{sys,ct}$	0.06735721363	0.999968
Heat exchangers (3 + 1)	$\lambda_{sys,hx}$	0.00002005474	$\mu_{sys,hx}$	0.71934096036	0.999972
Water pumps (3 + 1)	$\lambda_{sys,wp}$	0.00002190223	$\mu_{sys,wp}$	0.69021248646	0.999433
CRAHs (20 + 1)	$\lambda_{sys,CRAH1}$	0.00016601883	$\mu_{sys,CRAH1}$	0.00161823500	0.906953

* +1 represents the subsystem with one redundancy.

According to the above derivation, the failure rate and repair rate of the chiller subsystem could be obtained. Therefore, the four chillers can be seen as one block (subsystem) and the number of its states is greatly decreased from 2^4 to 2. Similarly, based on Markov model analysis, the RA properties of all redundant subsystems could obtain, including lake water pumps, chilled water pumps, cooling water pumps, cooling towers, heat exchangers, etc. The specific values of the failure rate and repair rate of each subsystem were summarized into Table 3. The above process greatly reduced the dimensions of whole system level.

3.2.2. Procedure for a series system or parallel system

Here, an example only including two components was selected to illustrate the failure rate and repair rate calculation process for the series and parallel system. The purpose is to obtain the calculation rules of the failure rate and repair rate for series and parallel system. The total number of states is equal to 4 (2^2), as shown in Table 4.

According to Eq. (3), the transition density matrix can be written to:

$$D=\begin{bmatrix} -(\lambda_1+\lambda_2) & \lambda_1 & \lambda_2 & 0\\ \mu_1 & -(\lambda_2+\mu_1) & 0 & \lambda_2\\ \mu_2 & 0 & -(\mu_2+\lambda_1) & \lambda_1\\ 0 & \mu_2 & \mu_1 & -(\mu_1+\mu_2) \end{bmatrix} \tag{19}$$

Where μ_1, μ_2 is the repair rate of component 1 and component 2, respectively. λ_1, λ_2 is the failure rate of component 1 and component 2, respectively. The steady state probability equations ($PD = 0$) are:

$$\begin{cases} -(\lambda_1+\lambda_2)p_1+\mu_1p_2+\mu_2p_3=0\\ \lambda_1p_1-(\mu_1+\lambda_2)p_2+\mu_2p_4=0\\ \lambda_2p_1-(\mu_2+\lambda_1)p_3+\mu_1p_4=0\\ \lambda_2p2+\lambda_1p_3-(\mu_1+\mu_2)p_4=0 \end{cases} \tag{20}$$

Then the state probabilities can obtain as:

$$\begin{cases} p_1=\frac{\mu_1\mu_2}{(\lambda_1+\mu_1)(\lambda_2+\mu_2)}\\ p_2=\frac{\lambda_2\mu_1}{(\lambda_1+\mu_1)(\lambda_2+\mu_2)}\\ p_3=\frac{\lambda_1\mu_2}{(\lambda_1+\mu_1)(\lambda_2+\mu_2)}\\ p_4=\frac{\lambda_1\lambda_2}{(\lambda_1+\mu_1)(\lambda_2+\mu_2)} \end{cases} \tag{21}$$

The OA of the series system is p_1 while that of the parallel system is $p_1 + p_2 + p_3$. The failure probability of the series system is $p_2 + p_3 + p_4$ while that of the parallel system is p_4. Meanwhile, the OA and failure probability also can be expressed by the system's failure rate and repair rate. Namely:

$$\begin{cases} \frac{\mu_{series}}{\lambda_{series}+\mu_{series}}=\frac{\mu_1\mu_2}{(\lambda_1+\mu_1)(\lambda_2+\mu_2)}\\ \frac{\lambda_{parallel}}{\lambda_{parallel}+\mu_{parallel}}=\frac{\lambda_1\lambda_2}{(\lambda_1+\mu_1)(\lambda_2+\mu_2)} \end{cases} \tag{22}$$

Where μ_{series}, $\mu_{parallel}$ is the repair rate of series system and parallel system, respectively. λ_{series}, $\lambda_{parallel}$ is the failure rate of series system and parallel system, respectively.

Any path is failed that leads to failure of the series system. Any path is repaired that leads to success of the parallel system. Consequently, the equivalent failure rate of series system and the equivalent repair rate of parallel system are respectively expressed to:

$$\lambda_{series}=\lambda_1+\lambda_2,\qquad \mu_{parallel}=\mu_1+\mu_2 \tag{23}$$

Combined Eq. (22) and Eq. (23), the equivalent repair rate of series system and the equivalent failure rate of parallel system are obtained, and can be simplified due to generally $\mu \gg \lambda$:

$$\begin{aligned} \mu_{series}&=\frac{\lambda_1+\lambda_2}{\lambda_1/\mu_1+\lambda_2/\mu_2+\lambda_1\lambda_2/\mu_1\mu_2}\approx\frac{\lambda_1+\lambda_2}{\lambda_1/\mu_1+\lambda_2/\mu_2}\\ \lambda_{parallel}&=\frac{(1/\mu_1+1/\mu_2)\lambda_1\lambda_2}{\lambda_1/u_1+\lambda_2/u_2+1}\approx(1/\mu_1+1/\mu_2)\lambda_1\lambda_2 \end{aligned} \tag{24}$$

Thus, the calculation rules of the failure rate and repair rate for series and parallel system (made up of two components) were obtained. The analysis can be promoted to the series or parallel system made up of n components.

3.2.3. Procedure for whole cooling system

As mentioned above, this proposed hybrid cooling system can operate in three discrete modes. In this Section, the RA properties of three operation modes were analyzed respectively. First, the RBD was further simplified by merging some subsystem, i.e. lake water pumps and heat exchangers merging into a lake cold sink, and cooling towers, cooling water pumps as well as chillers merging into a normal cold sink, as shown in Fig. 7. For normal cold sink, any failure of the subsystems (cooling towers, cooling water pumps as well as chillers) leaded to the failure of cold supply. Similarly, either lake water pumps or heat exchangers failure resulted in the failure of cold supply for lake cold sink. According to the calculation rules of series system, the RA properties of two cold sink subsystem could be assessed and shown in Table 5.

During *free cooling mode*, the cooling capacity of the lake water was large enough and larger than the maximum cooling load of data center. Moreover, the normal cold sink was designed to meet the peak cooling load. So, both cold sinks were able to remove the heat generated by data center individually. From the viewpoint of reliability and OA analysis, the cooling supplement from normal cold sink could be regarded as redundancy, as shown in Fig. 8 (a). The operation states are shown in Table 6. According to the calculation rules of parallel and series system, the failure rate, repair rate and OA of *free cooling mode* could be expressed as follows:

The failure rate is

Table 4
The operation states of an example system including two components.

	State			
	$State_{ex}$ 1	$State_{ex}$ 2	$State_{ex}$ 3	$State_{ex}$ 4
Component 1	1	1	0	0
Component 2	1	0	1	0
Series system	1	0	0	0
Parallel system	1	1	1	0

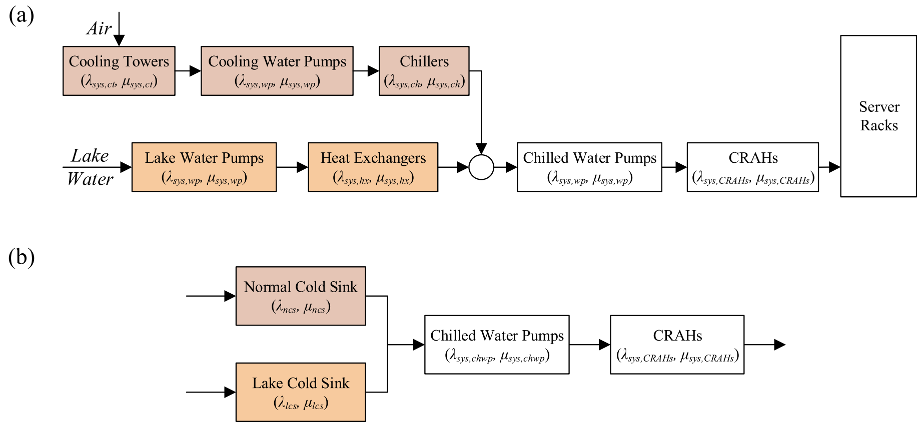

Fig. 7. System scheme of the hybrid cooling system.

$$\lambda_{fcm} = \lambda_{cs} + \lambda_{sys,chwp} + \lambda_{sys,CRAHs} = (1/\mu_{ncs} + 1/\mu_{lcs})\lambda_{ncs}\lambda_{lcs} + \lambda_{sys,chwp} + \lambda_{sys,CRAHs} \tag{25}$$

The repair rate is

$$\mu_{fcm} = \frac{\lambda_{cs} + \lambda_{sys,chwp} + \lambda_{sys,CRAHs}}{\lambda_{cs}/\mu_{cs} + \lambda_{sys,chwp}/\mu_{sys,chwp} + \lambda_{sys,CRAH}/\mu_{sys,CRAHs}} = \frac{(1/\mu_{ncs} + 1/\mu_{lcs})\lambda_{ncs}\lambda_{lcs} + \lambda_{sys,chwp} + \lambda_{sys,CRAHs}}{(1/\mu_{ncs} + 1/\mu_{lcs})\lambda_{ncs}\lambda_{lcs}/(\mu_{lcs} + \mu_{ncs}) + \lambda_{sys,chwp}/\mu_{sys,chwp} + \lambda_{sys,CRAHs}/\mu_{sys,CRAHs}} \tag{26}$$

The OA is

$$A_{fcm} = \frac{1}{(1/\mu_{ncs} + 1/\mu_{lcs})\lambda_{ncs}\lambda_{lcs}/(\mu_{lcs} + \mu_{ncs}) + \lambda_{sys,chwp}/\mu_{sys,chwp} + \lambda_{sys,CRAHs}/\mu_{sys,CRAHs} + 1} \tag{27}$$

where subscripts *fcm* represents *free cooling mode*. Subscripts *cs, ncs, lcs* represents cold sink, normal cold sink and lake cold sink, respectively.

During *normal cooling mode*, the lake water temperature was too high and not suitable to precool the hot return water from data center. The cooling load was totally handled by the normal cold sink. The operation states of the whole cooling system depended on the subsystems in normal cold sink path. As shown in Table 6, it could be seen that any failure of normal cold sink, chilled water pumps and CRAHs leaded to the failure of cooling supply. Therefore, the subsystems formed to a series system, as shown in Fig. 8 (b). The calculation rules of series system were applied and the RA properties of *normal cooling mode* could be calculated as follows:

$$\lambda_{ncm} = \lambda_{ncs} + \lambda_{sys,chwp} + \lambda_{sys,CRAHs} \tag{28}$$

The repair rate is

$$\mu_{ncm} = \frac{\lambda_{ncs} + \lambda_{sys,chwp} + \lambda_{sys,CRAHs}}{\lambda_{ncs}/\mu_{ncs} + \lambda_{sys,chwp}/\mu_{sys,chwp} + \lambda_{sys,CRAHs}/\mu_{sys,CRAHs}} \tag{29}$$

The OA is

$$A_{ncm} = \frac{1}{\lambda_{ncs}/\mu_{ncs} + \lambda_{sys,chwp}/\mu_{sys,chwp} + \lambda_{sys,CRAHs}/\mu_{sys,CRAHs} + 1} \tag{30}$$

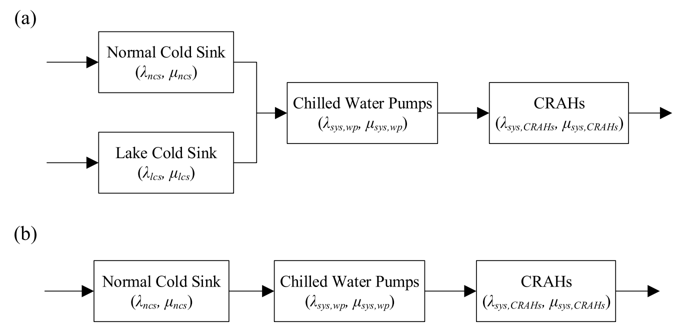

Fig. 8. Reliability scheme of the hybrid cooling system: (a) free cooling mode; (b) normal cooling mode or partial free cooling mode.

where subscripts *ncm* represents normal cooling mode.

During *partial free cooling mode*, the cooling system operated in partial free cooling mode when the cooling capacity of lake water could not cover fully the cooling load of data center. The hot return water was precooled firstly by the lake water and then flowed into the evaporator of chillers. The normal cold sink compensated the shortage of cooling demand. Note that even if the lake cold sink failed to provide cooling, the normal cold sink could completely deal with the heat generated by the data center and the cooling system was still in operation state. On the contrary, if normal cold sink failed, the free cooling sink did not have enough capacity to cool the data center and the cooling system operation fails. As shown in Table 6, the cooling requirement was satisfied as long as the normal operation mode is in operation state. The RBD of partial free cooling mode was the same as that of normal cooling mode. Thus, the RA properties of partial free cooling mode was the same as that of normal cooling mode.

$$\lambda_{pfcm} = \lambda_{ncm}, \quad \mu_{pfcm} = \mu_{ncm}, \quad A_{pfcm} = A_{ncm} \tag{31}$$

Where subscripts *pfcm* represents partial free cooling mode.

The RA properties of three operation modes were recorded in Table 7. The results shows that when the lake cold sink is large enough and the normal cold sink can be redundant. The OA of whole system under free cooling mode and normal cooling are 0.906927 and 0.906370 respectively. The OA slightly increases when adding

Table 5
The RA properties of two cold sink subsystems.

Subsystems	Failure rate		Repair rate		Operational availability
	Symbol	Value,/h	Symbol	Value,/h	
Normal cold sink	λ_{ncs}	0.000092503030	μ_{ncs}	0.136385784012	0.999322
Lake cold sink	λ_{lcs}	0.000041956970	μ_{lcs}	0.703835302948	0.999940

Table 6
The operation states of three operation modes.

States	Lake cold sink	Normal cold sink	Chilled water pumps	CRAHs	Free cooling	Normal cooling	Partial free cooling
$State_{ws}$ 1	1	1	1	1	1	1	1
$State_{ws}$ 2	1	1	1	0	0	0	0
$State_{ws}$ 3	1	1	0	1	0	0	0
$State_{ws}$ 4	1	1	0	0	0	0	0
$State_{ws}$ 5	1	0	1	1	1	0	Lack of cooling
$State_{ws}$ 6	1	0	1	0	0	0	0
$State_{ws}$ 7	1	0	0	1	0	0	0
$State_{ws}$ 8	1	0	0	0	0	0	0
$State_{ws}$ 9	0	1	1	1	1	1	1
$State_{ws}$ 10	0	1	1	0	0	0	0

Table 7
The RA properties of three operation modes.

Modes	Failure rate,/h	Repair rate,/h	Operational availability
Free cooling mode	0.00018795503	0.00183148648	0.906927
Normal cooling mode	0.00028042409	0.00271459119	0.906370
Partial free cooling mode	0.00028042409	0.00271459119	0.906370

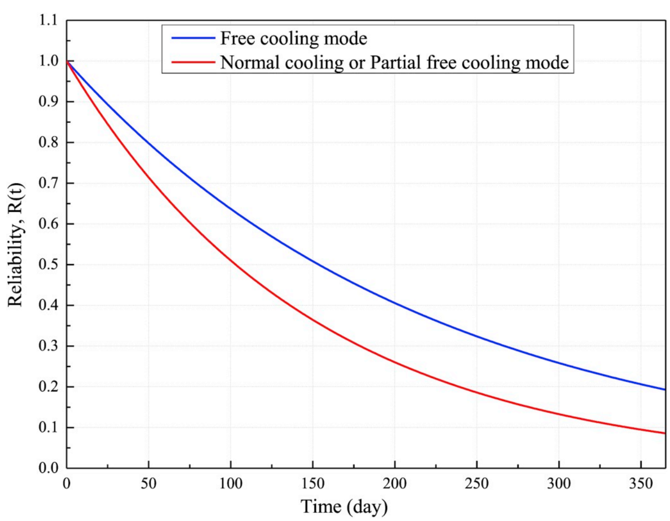

Fig. 9. System reliability of three cooling modes vs time.

redundancy in cold sink. But the failure rate of the free cooling mode drops by 64.22% and its reliability increases obviously, as shown in Fig. 9. Thus, we can conclude that this novel hybrid cooling system has better reliability performance than that of conventional chiller cooling system.

3.3. FA in event of cooling system operational failure

The ICT equipment working thermal environment can be maintained when the cooling system operate normally. But when the cooling system is in event of operational failure and the cooling capacity supplement is lower than the cooling load, the room temperature of data center starts rising. The set-point temperature of data center is usually set lower than the permissible temperature. Therefore, due to thermal inertia, it takes some time for the room temperature to exceed the permissible temperature. During this period, the cooling system still can be considered as functional available. In order to quantify the FA, it is necessary to accurately predict the future evolution of the room temperature, based on Eq. (4). According to the *2011 ASHRAE Thermal Guidelines* [8], the room temperature is recommended to be 18–27 °C for all Data Center Class and the upper limits for Class A1, Class A2, Class A3, and Class A4 are 32 °C, 35 °C, 40 °C and 46 °C respectively. Taking Class A1 for example, it is assumed that the ICT equipment working between 27 °C and 32 °C for a short time has no effect on them. Thus, the working temperature and permissible temperature are set to 27 °C and 32 °C, respectively.

Fig. 10 shows the evolutions of the room temperature with different heat densities in event of cooling system operational failure. In these simulation cases, assuming that: (1) the set-point of room temperature is 27 °C and the class is Class A1; (2) the cooling system operational failure lasts two mins; (3) the start-up time of cooling system, the time between cooling system restart and reaching rated cooling capacity, is set as two mins and the cooling capacity increases linearly during the start-up phase. Then, the FA can be calculated according to Eq. (7), and results are shown in Table 8. Among all cases, the cooling system always keeps available for ICT equipment with lower heat density (e.g. 0.25 kW/m^2, 0.5 kW/m^2) even if this operational failure appears. On the contrary, the IT Equipment in higher heat density data center (e.g. 1 kW/m^2, 2 kW/m^2, 3 kW/m^2, 4 kW/m^2) may be fatally flawed when this operational failure occurs. Additionally, it can be seen that the room temperatures rises almost linearly in the first few minutes of the cooling system operational failure and continues to rise during the first part of cooling system start-up. Even the same cooling system with the same reliability and OA, the FA varies with the characteristics of data center and deceases greatly as the heat density increases.

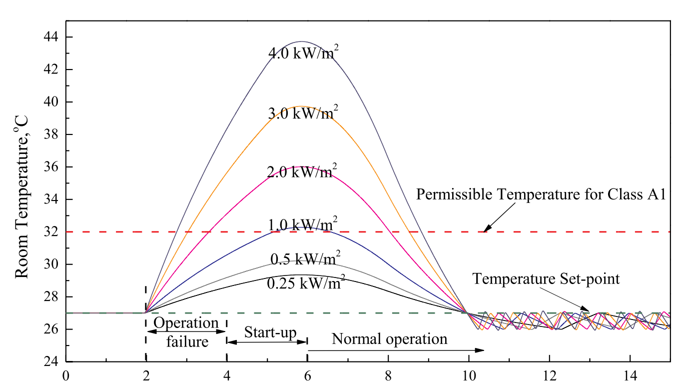

Fig. 10. Evolution of room temperature in event of a cooling system operational failure.

Table 8
The reliability, OA and FA for Class A1 with different heat densities.

Heat density, kW/m^2	Failure rate	Operational availability	Functional availability
0.25	0.00028042409	0.906370	1
0.5	0.00028042409	0.906370	1
1.0	0.00028042409	0.906370	0.872040
2.0	0.00028042409	0.906370	0.602073
3.0	0.00028042409	0.906370	0.533410
4.0	0.00028042409	0.906370	0.492838

4. Analysis and discussion

4.1. OA for redundant setting

Component with different redundancies were designed to calculate the whole system's OA. This section presented the impact of redundancy in CRAHs on the whole cooling system's OA. The RA properties of CRAHs subsystem with different CRAHs redundancies were summarized into Table 9, followed Section 3.2. The cooling system's OA with different redundancies in other components were also investigated but not presented for simplicity. According to Table 3, we can find that the CRAHs subsystem has the lowest OA among all subsystems.

Then the RA properties of three operation modes with different CRAHs redundancies were estimated, as shown in Fig. 11 and Table 10. It can be seen that the OA of whole cooling system is close to that of CRAHs subsystem. For example, the OA of free cooling mode with one redundancy in CRAHs is 0.906927 while that's value of CRAHs subsystem with one redundancy is 0.906953. Additionally, the OA of the whole cooling system obviously increases as the degree of redundancy in CRAHs increases (e.g., 0.906370 for one redundancy vs 0.986963 for three redundancies). It is an effective way to increase the overall system OA for adding redundancy to a component or subsystem with minimal OA.

Note that in design stage, if the OA is given, the redundancies of each component can be determined based on the following process: first, calculating the OA of all subsystems to find the one with minimum value; second, calculating the OA of the whole system; third, comparing it with the desired value, if the requirement is satisfied then ending the cycle, otherwise going to next step; finally, one component redundancy is added to the subsystem which has the minimum OA and back to the first step.

4.2. MADT analysis in the event of cooling system operational failure

Based on FA, we defined the *maximum allowable downtime* (*MADT*) as a new metric to quantify the repair time in the event of cooling system operational failure. It also can be used to quantify whether the repair time for cooling system is acceptable or not. MADT is equal to the maximum downtime of cooling system that keeps the room temperature within the permissible temperature. Specifically, a fault occurs that contributes to the operational failure of cooling system. But the cooling system can still be considered functionally available and no damage to ICT equipment if the fault can be repaired within the MADT; instead, the fault leads to incalculable damage to ICT equipment and data of data center. Thus, precisely MADT estimates for different data centers are helpful to the maintenance personnel to decide the repair time in the event of cooling system operational failure as well as the designer to optimize data center configuration. The relationships between the MADT and the start-up time of cooling system, the heat density, the room temperature set-point were studied in this Section. Note that we assumed that the capacity of cooling system increases linearly during the start-up phase.

Fig. 12 represents the MADT for different heat densities, Data Center Class and cooling systems with different start-up time. It clearly shows that the MADT drops with increasing heat density or start-up time of cooling system. Similarly, comparing lines with the same color in different subplots, it can be seen that the MADT drops greatly with decreasing room permissible temperature (i.e. different Data Center Class). Among them, heat density and Data Center Class have a greater impact on the MADT. We can use the following factors to increase the MADT: a. reducing the heat density (e.g. employ ICT equipment with lower heat density or reduce the number of ICT equipment); b. reducing the start-up time of cooling system (e.g. employ quick start cooling equipment or reducing the heat capacity of the cooling process); c. increasing the buffer temperature (e.g. reducing the operating set-point temperature or decreasing the Data Center Class). However, the investment costs and operation costs will increase. Specially, a low heat density usually follows low computational performance and large building space; a small start-up time of cooling system usually follows an expensive initial investment; a low room temperature set-point usually follows a high energy consumption of cooling system. Thus, according to Fig. 12, the tradeoff between the repair time and the heat density, start-up time of cooling system and Data Center Class can be determined to ensure the ICT equipment working in a safe thermal environment. Specifically, the safe thermal environment in terms of the dry-bulb temperature is 15–32 °C for A1, 10–35 °C for A2, 5–40 °C for A3, 5–45 °C for A4, according to *2011 ASHRAE Thermal Guidelines* [8].

5. Conclusions and future work

In this paper, we focused on the reliable performance evaluation method of a hybrid cooling system combining with lake water sink in data center. The FA was recommended as a new measure to assess the availability of data center cooling system, which integrated OA with specific function criteria. Based on RBD method, the complex system with multi operation modes could be divided into multilayer structure. That reduced the dimensions of Markov model and made it more practical to define all states and transition matrix. And the RA properties (i.e. the failure rate, repair rate and OA) of series, parallel and backup subsystems were deduced in detail and the calculation rules were obtained. Then, the RA properties of three operation modes were obtained based on the derivation-based calculation rules. Additionally, the *maximum allowable downtime* (*MADT*) was defined and evaluated for different heat densities, Data Center Class and start-up time of cooling system. The rest of conclusions are as follows:

(1) During *free cooling mode*, the lake water sink can fully cover the cooling load and the whole system's failure rate drops by 64.22%,

Table 9
The RA properties of CRAHs subsystem.

Subsystems	Failure rate		Repair rate		Operational availability
	Symbol	Value,/h	Symbol	Value,/h	
CRAHs (20 + 1)	$\lambda_{sys,CRAH1}$	0.00016601883	$\mu_{sys,CRAH1}$	0.00161823500	0.906953
CRAHs (20 + 2)	$\lambda_{sys,CRAH2}$	0.00011327457	$\mu_{sys,CRAH2}$	0.00334058065	0.967203
CRAHs (20 + 3)	$\lambda_{sys,CRAH3}$	0.00008687451	$\mu_{sys,CRAH3}$	0.00695014358	0.987655

* +1, +2, +3 respectively represents the subsystem with one redundancy, two redundancy, three redundancy.

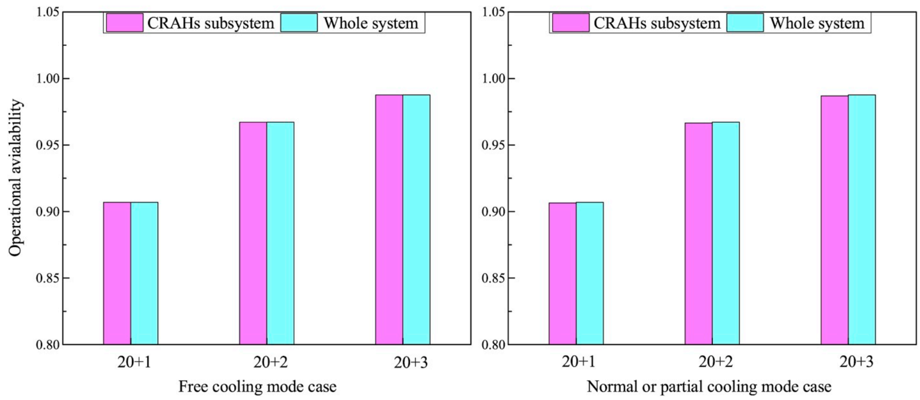

Fig. 11. Operational availability of different redundancy cases.

Table 10
The RA properties of three operation modes with different CRAHs redundancies.

Modes	CRAHs	Failure rate,/h	Repair rate,/h	Operational Availability
Free cooling mode	20 + 1	0.00018795503	0.00183148648	0.906927
	20 + 2	0.00013521077	0.00398376836	0.967174
	20 + 3	0.00010881071	0.00868301442	0.987624
Normal or partial free cooling mode	20 + 1	0.00028042409	0.00271459119	0.906370
	20 + 2	0.00022767983	0.00657680165	0.966540
	20 + 3	0.00020127977	0.01523732888	0.986963

i.e. the reliability greatly increases versus *normal cooling mode.* This means that this novel hybrid cooling system has better reliability performance than that of conventional chiller cooling system.

(2) The whole system's OA converges to the subsystem with minimal OA (e.g. 0.906953 for CRAHs subsystem vs 0.906370 for whole cooling system). It can significantly increase by adding the redundancy to the subsystem with minimal OA, (e.g. 0.906370 for one redundancy vs 0.986963 for three redundancies). This provides the principle of redundant design.
(3) The *maximum allowable downtime* (*MADT*) can be used to quantify whether a repair duration is acceptable or not in event of cooling system failure. The MADT analysis provides the principle of improvement FA. The tradeoff between the repair time and the heat density, start-up time of cooling system and Data Center Class can be determined to ensure the ICT equipment always working in a safe thermal environment.

This work assumed that any component or subsystem of the cooling system only have two states (on/off). For example, in a system with four

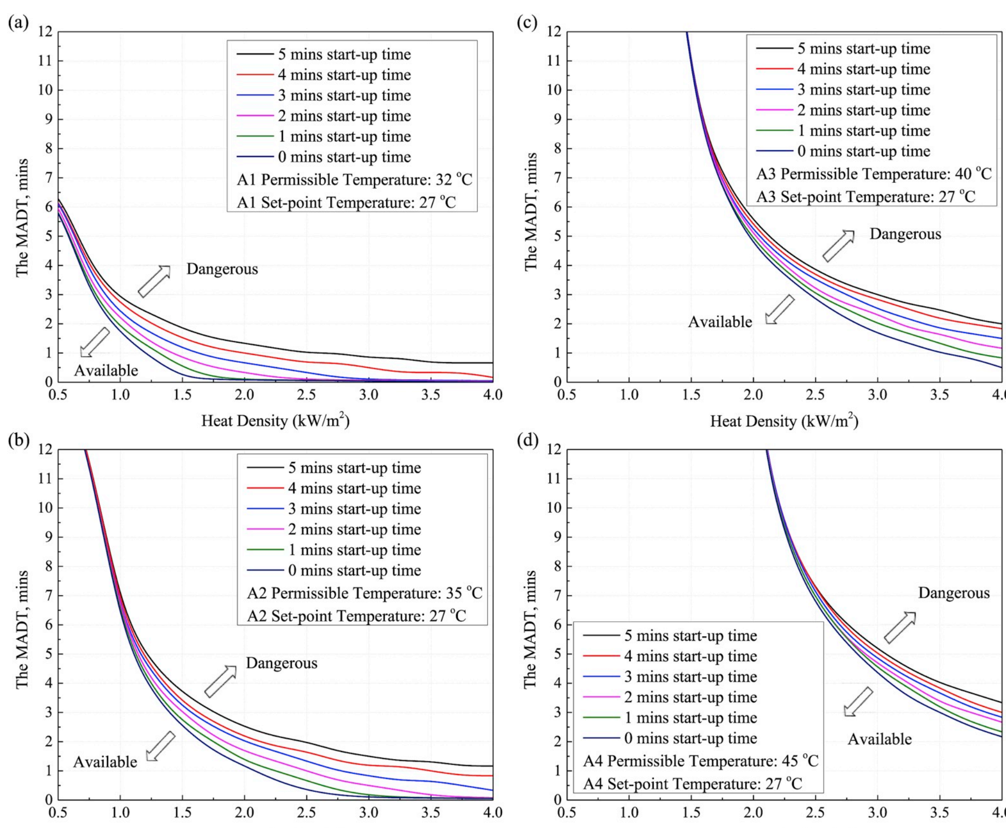

Fig. 12. The MADT in different scenarios: (a) Class A1; (b) Class A2; (c) Class A3; (d) Class A4.

chillers installed (i.e. three chillers serve as the basic chillers and another one serves as a redundancy), if two or more chillers fail, the cold supply from chillers is set as completely failure. In future, the FA for the case with insufficient cold supply will be further investigated and we can find more detailed relationship between the reliability performance and the type of failure.

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