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Equation-based Object-oriented Modeling and Simulation of Cooling Systems in Data Centers

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Abstract

Cooling infrastructures contribute about 50% of total energy consumption in a typical data center. Computer models are pivotal in designing and optimizing energy-efficient cooling systems to reduce excessive cooling energy consumption. Compared to the conventional building energy simulation tools, equation-based object-oriented modeling language Modelica is an emerging approach that can enable fast modeling and simulation of the dynamic cooling system in data centers. In this paper, we introduce a newly developed open source data center package in the Modelica Buildings library to support the fast modeling and simulation of cooling and control systems of data centers. The data center package contains major thermal and control component models, such as Computer Room Air Handler, Computer Room Air Conditioner, models of different subsystem configurations such as chillers with differently configured waterside economizer, as well as templates for different systems. Furthermore, we utilize the new package to perform a case study on the operation of a cooling system in the data center. In this case study, we investigate the performances of the cooling system under normal conditions and emergency situations such as blackout. The case study shows that the dynamic modeling and multi-domain co-simulation in the Modelica-based tool make it convenient for users to investigate not only the thermal performance but also the electrical performance of the data centers.

Keywords: Equation-based Modeling, Waterside Economizer, Data Center, Emergency Operation

1 Introduction

Data centers are critical, energy-intensive infrastructures that support the fast growth of the information technology (IT) industry and the transformation of the economy at large. In 2010 data centers consumed about 1.1% to 1.5% of the total worldwide electricity and the number was about 1.7% to 2.2% for the U.S. [1] . The energy in data centers is mainly consumed by two parts: IT equipment (e.g., servers, storage, network, etc.) and infrastructure facilities (e.g., cooling system). The latter usually account for about half of the total energy consumption in a typical data center [2].

Modeling and simulation is a cost-effective way to evaluate the design and operation of the cooling systems. Modeling refers to the process that the real physical system is represented as mathematical models. Different physical systems (thermal, electrical, and electromagnetic, etc.) with different time-scaled dynamics are involved. This usually leads to high-indexed differential algebraic equations. Simulation is then conducted to numerically solve the mathematical equations in order to calculate the unknowns, which involves computer representation of models, different numerical solvers, and solution procedures.

Many tools have been developed in academia and industry to perform computer modeling and simulation of the cooling systems in data centers. For example, eQuest [3], EnergyPlus [4] [5], TRNSYS [6], and some customized simulation tools such as Energy Modeling Protocol [7] have been used to study the cooling systems with waterside economizers (WSEs) and airside economizers (ASEs) in data centers. Most of these traditional tools are based on imperative programming languages such as FORTRAN and C/C++. When implementing a physical model in these tools, model developers utilize their expertise to sort the physical equations in an order so that the unknowns (model outputs) in the equations can be solved based on given known variables (model inputs). The nonlinear equations are usually manipulated to be solved iteratively, and the differential equations are discretized to numerically approximate the state variables. Then, the model developers write the manipulatively sorted variable assignments into computer source codes. Other computer program procedures may be called in the source codes to calculate the input variables from a subsystem at each time step, which might request from the solver re-simulation of a subsystem iteratively [8].

The above-mentioned conventional simulation tools expose several disadvantages in terms of their modeling and simulation performance. First, in the imperative programming languages, mathematical equations are typically intertwined with numerical solvers. For example, a typical zone model is mathematically described as a first-order differential equation as shown in Eq.(1), where m is the zone air mass, $C_{p,a}$ is the specific heat capacity of the air, T_{zone} is the zone air temperature, t is time, d is the total derivative, and Q_i is the ith heat source in the zone.

$$mC_{p,a}\frac{dT_{zone}}{dt} = \sum_{i=1}^{n} Q_i(T_{zone}) \tag{1}$$

In EnergyPlus that is written in C++, the zone model is represented by discretizing the differential term on the left side over time. One of the discretization algorithm used for the zone model is the 3rd-order backward difference formula, which converts the differential equation into a set of algebraic equations as shown in Eq.(2).

$$mC_{p,a}\frac{\frac{11}{6}T_{zone}^{t}-3T_{zone}^{t-\delta t}+\frac{3}{2}T_{zone}^{t-2\delta t}-\frac{1}{3}T_{zone}^{t-3\delta t}}{\delta t} = \sum_{i=1}^{n} Q_i(T_{zone}^{t}), \tag{2}$$

where δt is the length of the time step, and subscripts t,..., $t-3\delta t$ represent the time instance. The numerical method is integrated with the mathematical equations in the source codes, which leads to a program code that is hard to maintain. By accepting non-convergent solutions at intermediate time steps to the simulation results, the nested solver can also introduce numerical noises that can pose challenges to the optimization programs [8]. Second, some platforms are not designed for evaluating the system dynamics and the semantics of their control have little in common of how actual control works [9]. For example, in EnergyPlus, the commonly used Proportional-Integral (PI) control loop is assumed to be ideal, i.e., there will be no overshoot. EnergyPlus also idealizes dead band or waiting time, which are frequently used in the building control process. Moreover, many equipment models have built-in idealized control that requests flow rates, and flow rates are ideally distributed within a system rather than the results of friction-based flow distribution. This makes it difficult to model, test and verify actual control. Third, different numerical solvers for differential equations might be needed for different user cases [10]. However, most traditional tools have predefined solvers in their physical component models. Forth, these tools are hard to support fast prototyping based on various user's needs. For example, the control logic for the WSE in DOE2.2 are predefined. Users are able to change the thresholds of particular conditions, but not the logic themselves. It is difficult for users to implement new logic. Fifth, these tools are difficult to perform multi-domain simulations. For example, to study the interactive performance of the thermal and the electrical system, one needs an external data synchronizer to couple these tools with electrical simulation tools [11] .

Equation-based language such as Modelica [12] can provide solutions to the above-mentioned issues. Modelica separates physical equations and numerical solvers wherever possible. The separation can mitigate the risks of intertwinement, and can fully take advantages of different expertise from different domains. For example, model developers can concentrate on how to develop efficient high-fidelity physical models, while computer engineers can focus on the development of robust numerical solvers. Also, the State Graph package [13] in Modelica Standard Library can be used to perform discrete control which contains dead band or delay time. The rich library of numerical solvers in Modelica can be chosen for different systems and different use cases. Besides, Modelica models are convenient enough to be extended to support fast modeling and simulation. Furthermore, Modelica itself supports multi-domain simulation. Models from different domains are built in one single platform so that dedicated data synchronizer between different platforms is not required.

Modelica Buildings library is designed to model and simulate the detailed cooling and control system at building and community level [14]. The Buildings library is free open-source, and has been demonstrated to have full capability to conduct energy efficiency analysis. Researchers have been active to utilize the Buildings library in a broad range of applications, such as dynamic modeling of a theater [15], rapid prototyping of a district heating system with arbitrary topologies [16], evaluation of feedback control [8], fault detection and diagnosis at the whole building level [17], optimal model-based control design and evaluation [18, 19], as well as coupled simulation between the cooling system and the detailed room model with fluid dynamics considered [20] [21].

This study further extends the Modelica Buildings library to support fast modeling and simulation of cooling systems for data center applications. As some of the data center cooling systems, such as chiller plants, are also commonly used by large commercial buildings and district cooling systems, the models developed by this study can also be used for those applications. This paper first introduces typical air-cooled cooling systems in data centers such as chilled water system and direct expansion (DX) system. In Section 3, we give an introduction of the component models, subsystem models, cooling control models, and system models in the data center package. In Section 4, to demonstrate the capability of Modelica-based tools, we model and simulate a data center cooling system under normal operation and emergency operation. We then conclude the paper in Section 5.

2 Air-cooled Cooling Systems in Data Centers

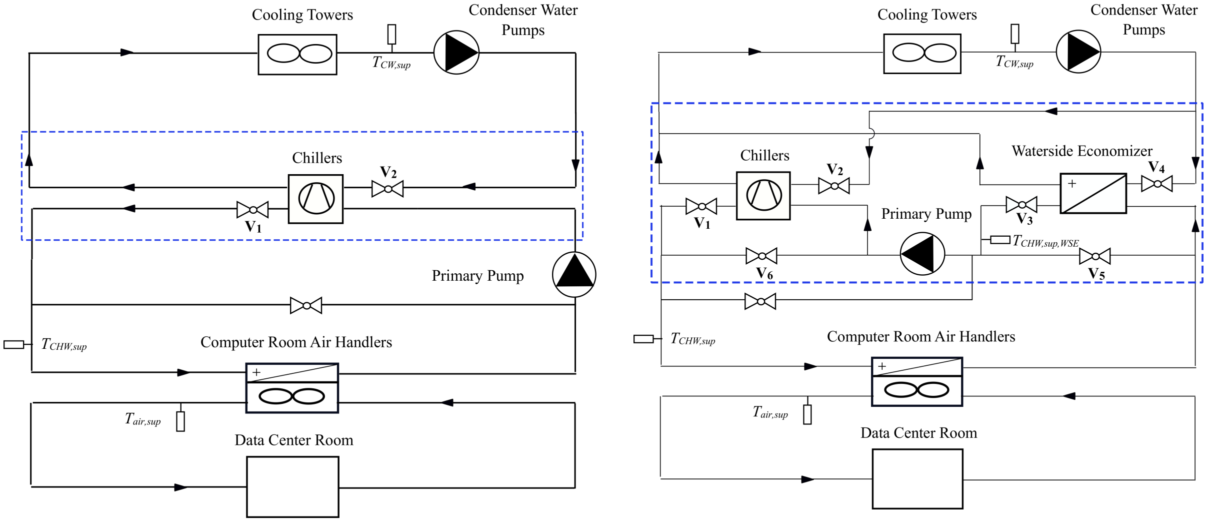
Many different cooling systems have been designed and operated for data center usage. The data center room can be cooled by air, single- or two-phase liquid at room, rack or even chip level. However, the majority of existing data centers are cooled by air [22]. Thus, our current modeling efforts focus on the air-cooling system. The air-cooled system supplies to the data center room the cold air, which is then drawn by the rack or servers [23]. The air can be cooled by chilled water system or DX system, which are introduced in this section.

2.1 Chilled Water System

Chilled water system is usually used for large data centers. A typical chilled water system include chillers, CRAHs, pumps, and cooling towers, as shown in Figure 1(a). The heat generated in the data center room is first transferred to the chilled water through the CRAHs, and the chillers then transfer the heat from the chilled water loop into the condenser water loop through a refrigeration system. The cooling towers at last reject the heat in the condenser water loop to the outdoor environment.

Economizers can also be installed to provide auxiliary cooling when outdoor condition allows. The economizers can be equipped on either air side or water side of the chilled water system. If on the water side, it is typically called as waterside economizer (WSE). WSE can be configured with chillers in different ways [9]. For example, the WSE can be integrated with chillers, meaning that the economizer can meet all or some of the load while the chiller meets the rest of the load, or non-integrated, meaning the economizer can only operate when it can meet the entire load.

A common configuration of the chiller plant with integrated WSEs is shown in Figure 1(b). The WSE is located on the load side of the common leg rather than the plant side. This configuration can guarantee that the WSE can meet the warmest return chilled water and maximize the number of hours when WSE can operate. The chiller plant with integrated WSEs can operate in three modes: Free Cooling (FC) mode when only WSEs are enabled for cooling, Partial Mechanical Cooling (PMC) mode when the chillers and WSEs are both triggered, and Full Mechanical Cooling (FMC) mode when only the chillers are activated. When a particular cooling mode should be activated is determined by a cooling mode controller, as described in Section 3.3.1, and how to achieve the cooling mode is determined by the manipulation of the associated isolation valves $V_1 \sim V_4$, the chiller bypass valve (V_6) and the WSE bypass valve (V_5), as shown in Section 3.3.3.



(a) Without WSE

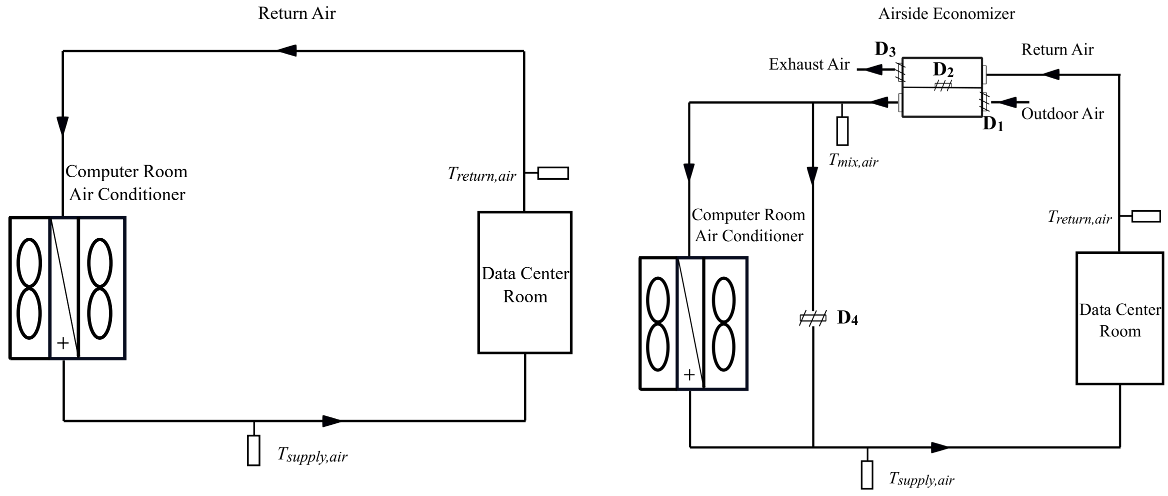
(b) With an integrated WSE on the load side

Figure 1. Primary-only chilled water system

2.2 DX System

DX system is widely used in small data centers as a primary cooling system or as a backup system for the chilled water system. The major cooling source in a DX system is the Computer Room Air-Conditioner (CRAC) units. CRAC units typically have their own refrigeration system. They absorb heat from the data center room through evaporators, and reject heat to the outdoor environment (air-cooled CRAC) or a condenser water loop (water-cooled CRAC) through condensers. Based on the type of the condenser in the CRAC, the DX system is categorized into two classes: air-cooled and water-cooled. Figure 2(a) shows a schematic drawing for an air-cooled DX system, where the air-cooled CRAC is installed to cool the return air and send it back to the data center room. The DX system is usually installed together with air side economizers (ASEs), for example, as shown in Figure 2(b). The ASEs enable the system to efficiently use the cold outdoor air and reduce the operating time of CRACs.

In Figure 2(b), with ASEs, the air-cooled DX system can also operate in the three modes mentioned in Section 2.1. The only difference is that the mechanical cooling is provided by the CRACs in the air-cooled DX system instead of the chillers as in the chilled water system. Similarly, when to activate a particular cooling mode is determined by the cooling mode controller, and how to achieve the cooling mode is determined by the manipulation of the dampers such as $D_1 \sim D_4$ in Figure 2(b)[9].



(a) Without ASE (b) With an ASE

Figure 2. Air-cooled DX system

3 Model Implementation

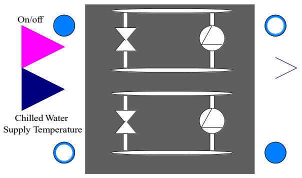
The data center package *Buildings.Applications.DataCenters* was publicly released in the Modelica Buildings library 5.0.0 (https://simulationresearch.lbl.gov/modelica/) in December 2017. It contains component models for the above-mentioned two typical air-cooled cooling systems in data centers. This package adopts the class hierarchy used by the Buildings library, and contains various reusable base classes. These base classes together with the inheritance and instantiation in the object-oriented modeling language Modelica facilitate fast modeling and simulation of data center cooling systems. The following part introduces some of the key models for cooling components, subsystems, controls and system templates.

3.1 Cooling Component Models

3.1.1 Group of Equipment

A group of identical chillers and pumps can be modeled via the vectorization of existing chiller and pump models, respectively. The vectorized equipment model is assigned with the same design parameters but different performance curves if needed. The pseudo-code of vectorized chiller model *ElectricChillerParallel* in Modelica is shown in Figure 3(a). First, a partial class of the electric chiller model *Fluid.Chillers.BaseClasses.PartialElectric* is instantiated through vectorization with a number n, which specifies the length of the array chiller. The keyword *replaceable* allows the model to be redeclared with a detailed chiller model later on. Line 3 specifies the medium used in the chillers. Line 4 defines the identical design parameters for the chillers with the keyword *each* in Modelica, such as the design capacity. Line 5 defines the performance curves of each chiller by pointing different curves from a performance curve array. The same instantiation method is also used to model a group of pumps. In addition, we add isolation valves in the vectorized models to avoid circulating flow among components. The implemented source code is packaged under the graphic icon as shown in Figure 3(b).

```
1: replaceable Fluid.Chillers.BaseClasses.PartialElectric chillers[n]
2: constrainedby Fluid.Chillers.BaseClasses.PartialElectric(
3:      redeclare each final replaceable package Medium = Medium,
4:      each final parameters = parameters,
5:      final performanceCurve = performanceCurveArray)
6: "Chillers with identical design parameters but different performance curves"
```



(a) Pseduo codes

(b) Modelica icon

Figure 3. Vectorized chiller model in Modelica

3.1.2 Waterside Economizer

The WSE model is built on a heat exchanger model with constant effectiveness, and a three-way valve model (Figure 4). The three-way valve is on the chilled water side, and can be adjusted to control the chilled water supply temperature by a built-in PI controller. The three-way valve can be activated or deactivated based on users' needs for different control strategies. For example, in the FC mode, the mechanical cooling is shut down, and only WSE is activated to provide cooling. The chilled water supply temperature at the downstream of the WSE can be controlled at its set point by regulating the speed of cooling tower fans or modulating the three-way valve on the chilled water side in the WSE. The former control strategy requires deactivation of the three-valve, while the latter control needs to activate the three-way valve. The switch between activation and deactivation of the three-way valve is realized by setting the Boolean parameter *activateControl* to *True* or *False*.

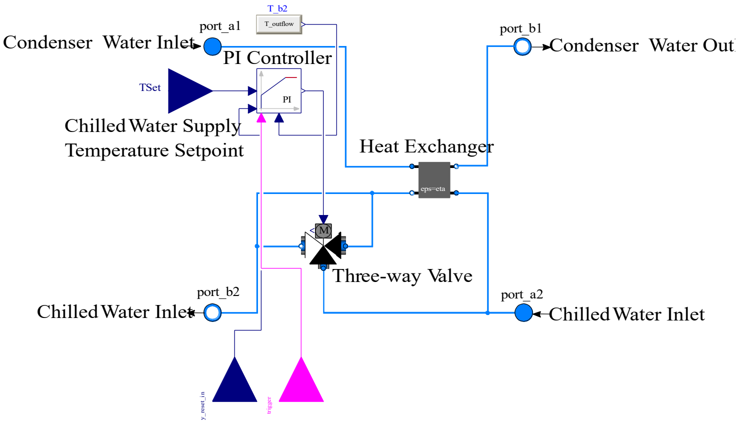


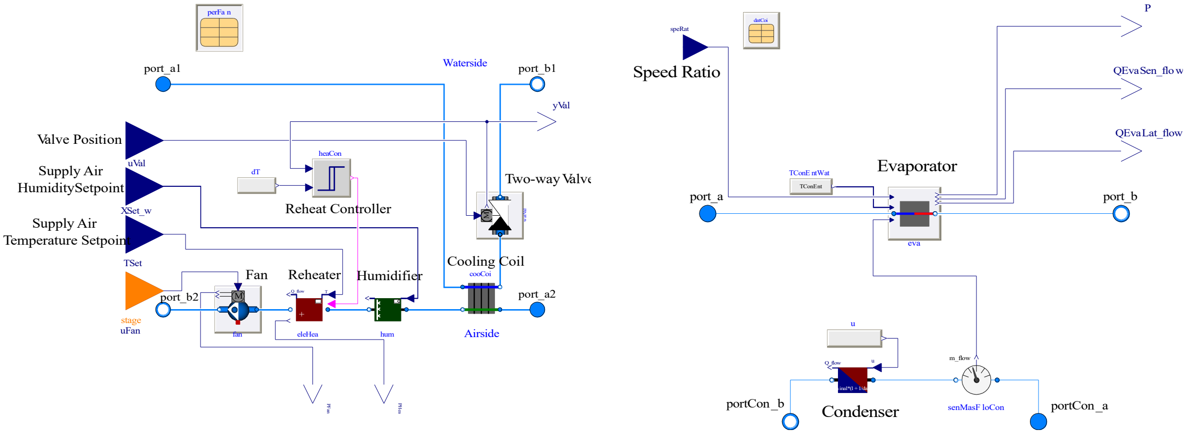
Figure 4. Waterside economizer model in Modelica

3.1.3 Computer Room Air Handler

As shown in Figure 5, the CRAH model named *CoolingCoilHumidifyingHeating* built on the existing models of a cooling coil, a humidifier, an electric reheater, a fan and a two-way valve on the water side of the cooling coil. A hysterical on/off controller is added to for the electrical reheater in order to avoid simultaneous heating and cooling.

3.1.4 Computer Room Air Conditioner

Both air-cooled and water-cooled CRAC models are built in Modelica Buildings library. The capacity of the refrigeration system in the CRAC is expressed as regression equations based on inlet temperature and flowrate on both evaporator and condenser sides. Detailed equations can be referred to Ref. [24].



(a) CRAH model (b) CRAC model

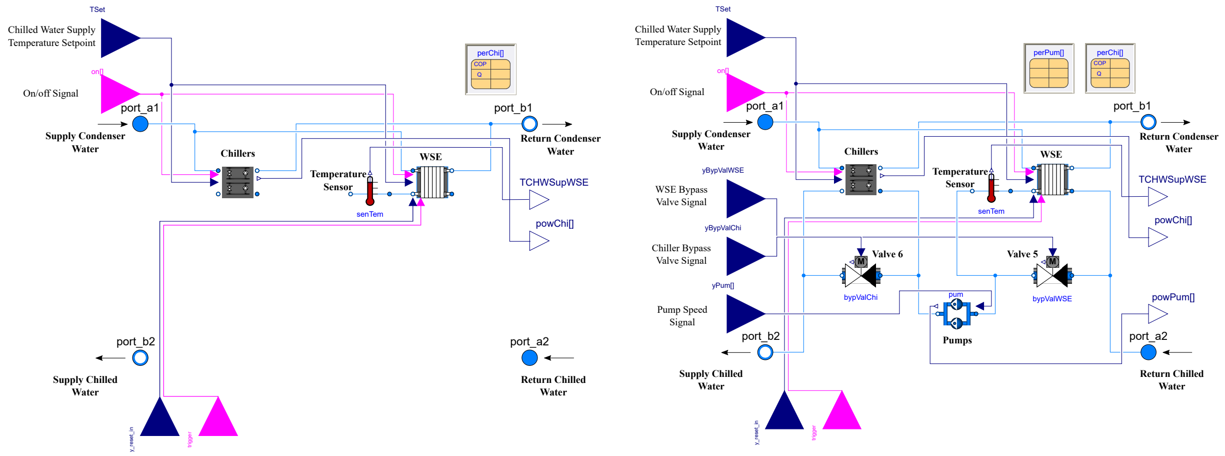
Figure 5. Modelica Implementation

3.2 Subsystem Models

Different subsystem models and their base classes in terms of the arrangement of chillers and WSEs are also built in this package [9]. The different subsystem models share the same base class as shown in Figure 6(a). The base class is built on a four-port fluid interface, representing the inlets and outlets for the chilled and condenser water, with instances of the chiller group model and the WSE group model. The connections of chillers and WSEs on the chilled water side are not initiated in the base class, because different subsystem models mentioned in Ref [9] have different configurations of connections.

The different subsystems can then be modelled individually using a hierarchical approach. In this case, we first inherit the base class, then instantiate additional necessary equipment models, and finally add physical connections among components. For example, to model the subsystem where the WSEs are integrated on the load side of a primary-only chilled water system (as shown in the dash box of Figure 1(b)), we only need to extend the base class, add necessary instances such as bypass valves and pumps, expose model inputs and outputs, and finally connect them as in an actual system. Figure 6(b) shows the implementation of such a subsystem model based on the base class in Figure 6(a). On the left are the model inputs, including the on/off command, supply chilled water temperature setpoint, bypass valve position signal and pump speed signal from particular controllers. On the right are the model outputs, such as power from chillers and pumps.

Taking advantage of object inheritance, and instantiation in the object-oriented Modelica, this hierarchical modeling structure allows users to manage the complexity of large models, and to assemble system models as one would connect components in an actual system. This structure also facilitates debugging and verification of component models. For example, a lower-level model is first debugged and verified, and then instantiated in a higher-level model, which can help identify modelling errors at the early stage of the model development.



(a) Base class

(b) Integrated WSE on the load side

Figure 6. Modelica implementation of chillers and WSE subsystem

3.3 Control Models

3.3.1 Cooling Mode Control

As described in Section 2, in both the chilled water and DX systems, a cooling mode control determines when to activate and deactivate the FC, PMC and FMC modes for the cooling system with economizers based on the system status and the environment. The cooling mode control usually serves as a supervisory control, and the output control signal will be taken as inputs by other equipment-level controllers as described in Section 3.3.2.

The cooling mode can be abstractly described as a finite-state machine. The cooling mode can transition from one state to another in response to some external inputs. For example, we can present a widely-used control strategy [25] for a chilled water system with integrated WSEs using a state graph as shown in Figure 7(a). The chiller is switched on if

$$\Delta t_{chi,off} \geq \Delta t_1 \ \ and \ \ T_{chw,sup,wse} > T_{chw,sup,set} + \Delta T_1 \ for \ \ \Delta \mathrm{t}_2, \tag{3}$$

and switched off if

$$\Delta t_{chi,on} \geq \Delta \mathrm{t}_3 \ \ and \ \ T_{chw,sup,wse} < T_{chw,sup,set} - \Delta T_2 \ for \ \ \Delta \mathrm{t}_4, \tag{4}$$

where $\Delta t_{chi,off}$ is the time of the chiller in Off status, $\Delta t_{chi,on}$ is the elapsed time since the chiller was switched on. The $\Delta t_1 \sim \Delta t_4$ are time thresholds whose defaulted values are shown in Figure 7(a). $T_{chw,sup,wse}$ is the temperature of the supply chilled water at the downstream of the WSE, $T_{chw,sup,set}$ is the chilled water supply temperature set point, and ΔT_1 and ΔT_2 are the deadband temperature. The waiting time and dead band can prevent frequent staging operations.

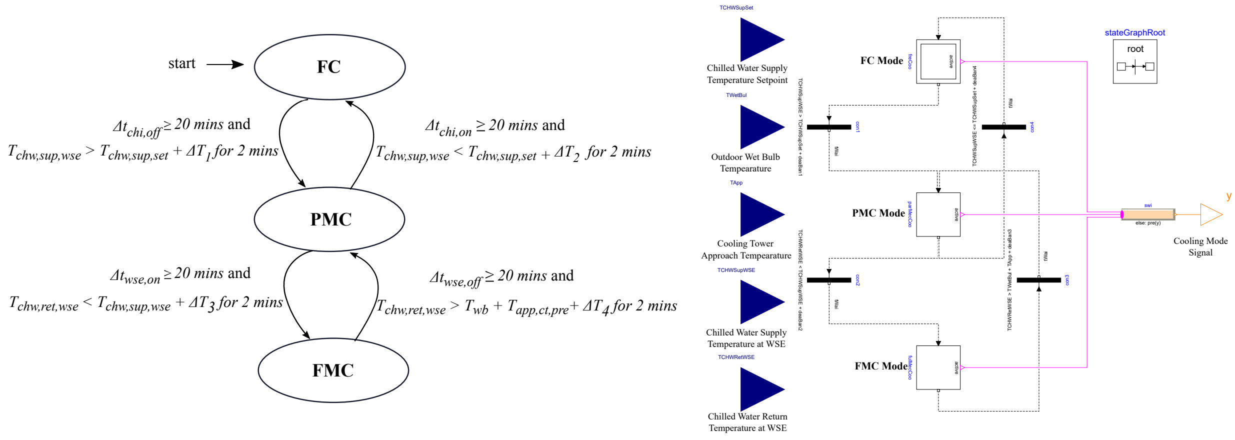
The WSE is enabled when

$$\Delta t_{wse,off} \geq \Delta t_7 \ \text{and} \ T_{chw,ret,wse} > T_{wb} + T_{app,ct,pre} + \Delta T_4 \ for \ \ \Delta t_8, \tag{5}$$

and is disabled when

$$\Delta t_{wse,on} \leq \Delta t_5 \ \text{and} \ T_{chw,ret,wse} < T_{chw,sup,wse} + \Delta T_3 \ for \ \ \Delta t_6, \tag{6}$$

where $\Delta t_{wse,off}$ is the passed time of the WSE in Off status, $\Delta t_{wse,on}$ is the elapsed time since the WSE was switched on, $T_{chw,ret,wse}$ is the temperature of the return chilled water at the upstream of the WSE, T_{wb} is wet bulb temperature of the outdoor air, $T_{app,ct,pre}$ is the predicted approach temperature of the cooling tower, ΔT_3 and ΔT_4 are the offset temperature, and the $\Delta t_5 \sim \Delta t_8$ are time thresholds. In our application, we set $T_{app,ct,pre}$ as the nominal approach temperature in the cooling tower, although many other prediction algorithms can be used such as using a detailed cooling tower model [25], or engineering experience [26]. Figure 7(b) shows the Modelica implementation using State Graph package.



(a) State graph (b) Modelica implementation

Figure 7. Cooling mode control for a chilled water system with integrated WSEs

3.3.2 Equipment Control

Equipment-level control includes stage control and speed control of chillers, pumps and cooling towers. The stage control determines when and how many equipment are activated at a given time. The speed control regulates the speed of equipment such as cooling tower fans.

For the stage control of chillers, we adopted the following logic: If the cooling mode control outputs the FC mode, then all the chillers should be commanded off. If the cooling mode control outputs the PMC or FMC mode, at least one chiller should be active all the time. One additional chiller is commanded on when

$$Q_{ave} > Q_{up} + \Delta Q \ \text{ for } \ \Delta t_9, \tag{7}$$

and commanded off when

$$Q_{ave} < Q_{down} - \Delta Q \ \text{ for } \ \Delta t_{10}, \tag{8}$$

where Q_{ave} is the average cooling load in all the active chillers at current time, Q_{up} and Q_{down} are the cooling load thresholds for staging up and down, respectively, and ΔQ is a deadband. The two conditions need to remain true for a predefined waiting time Δt_9 and Δt_{10}, respectively. The stage control was implemented in Modelica using the state graph.

For the speed control, here we take the cooling tower fans as an example. The cooling tower fan speed should be regulated differently in different cooling modes. One possible set of control logics is shown as follows.

- In the FC mode, the fan speed is controlled to maintain a predefined chilled water supply temperature at the downstream of WSE.
- In the PMC mode, the fan speed is reset to 90% all the time. Setting the speed to 100% can produce the condenser water as cold as possible and maximize the WSE output. However, with variable speed drives on the tower fans, the changes from 90% to 100% does little to lower the condenser water temperature but increases the fan energy significantly [25].
- In the FMC mode, the fan speed is controlled to maintain the supply condenser water at its

set point.

3.3.3 Valve Control

The transition among each cooling mode is achieved by manipulating the associated isolation valves and bypass valves. For example, in Figure 1(b), when the cooling system is in the FC mode, the isolation valves $V1$ and $V2$ in chillers, and $V5$ for bypassing the WSE are shut off. The isolation valves $V3$ and $V4$ in the WSE, and $V6$ for bypassing the chillers are fully opened so that the chilled water can flow through the WSE, and then be delivered by the primary pumps to the CRAHs. In the PMC mode, $V1$ and $V4$ are fully open, and $V5$ and $V6$ are shut off. In the FMC mode, while $V3, V4$ and $V6$ are shut off, $V1, V2$ and $V5$ are fully open to deliver the chilled water through the primary pumps, chillers, and then CRAHs.

3.4 System Templates

Templates for different systems are also provided. An example is shown in Figure 8, where the model of a primary-only chilled water system with an integrated WSE, its control system, boundary conditions, and post-processor is presented.

The boundary conditions for the cooling system are read from an external weather file. The cooling and control system are assembled by connecting the above-mentioned component and control models. The data center room model in the cooling system is simplified using a well-mixed volume, because the air flow management in the room is not the focus here. The cooling load is assumed to be constant during the simulation period. Post-processing provides an option to process the simulation results such as energy and control performances in the model. The simulation results of the system template model can be refereed in Ref [9].

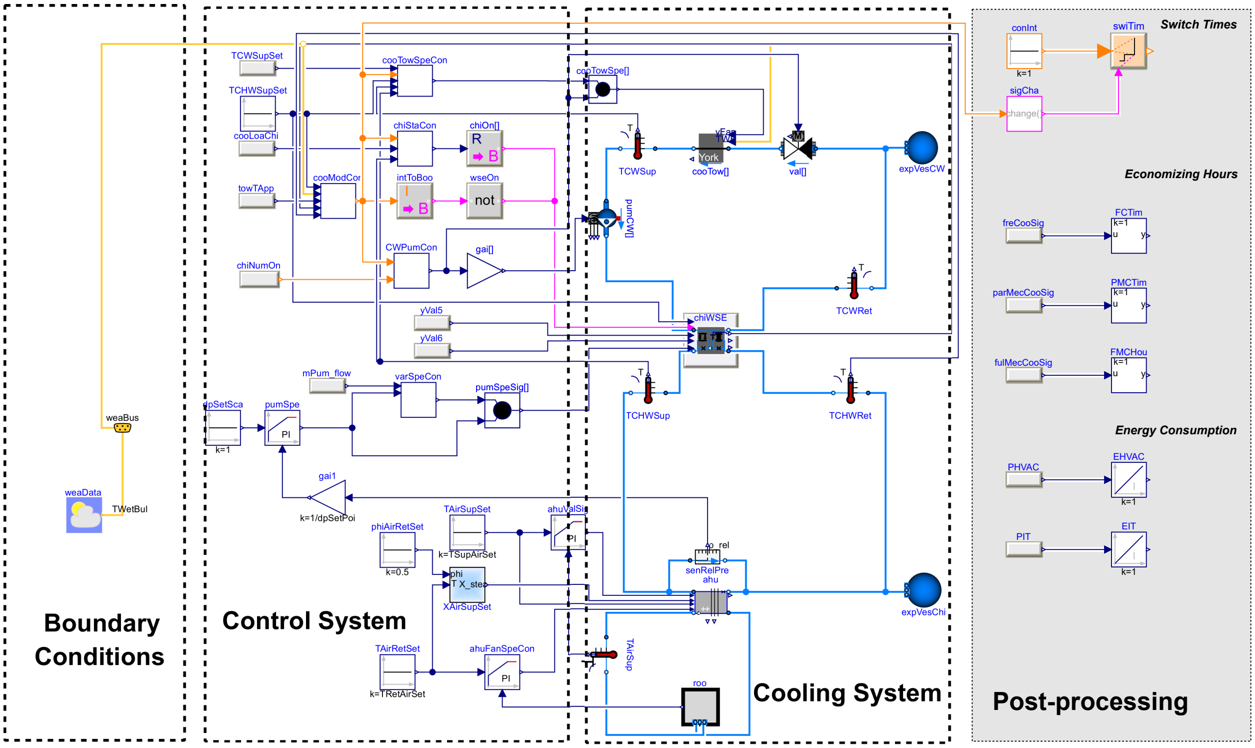


Figure 8. Modelica implementation of a primary-only chilled water system with an integrated WSE

3.5 Model Evaluation

Each component is verified in a simulation example, following the conventions of the Buildings library mentioned in [10]. Taking advantages of the class hierarchy in the Buildings library and the object-oriented language Modelica, we built the data center package based on the base classes and ready-to-use component models in the Buildings library. We validated the data center package using analytical verification and comparative testing. The former has also been used to validate all individual component models in the Buildings library. For example, the WSE model is validated by analytical verification, which compares its results with analytical solutions that are derived for certain steady-state or transient boundary conditions. In addition, the CRAC model in Modelica is validated by comparing its simulation results with the same model in EnergyPlus.

4 Case Study: Data Center Operation

To demonstrate the usage of the newly implemented Modelica models for data center, we studied data center cooling using the Modelica models. This section studied two scenarios to investigate the cooling system operation in a virtual data center located in Salem, Oregon, USA, which is ASHRAE climate zone 4C. The first scenario investigates the energy efficiency and control performance of the cooling system under normal operation (e.g. connected to grid), and the other one compares different operation strategies to explore the opportunities of effectively operation of the cooling system under emergency situations (e.g. disconnected from grid and backup generators).

4.1 Description of Cooling and Electrical System

Data centers are required to operate 24 hours per day, 365 days per year. Electrical distribution system in data centers is designed to power IT equipment in a safe and reliable manner. One typical design is to power the data center with multiple sources. For example, the data centers normally draw three-phase AC power from the power grid, and uses diesel generators as backups during power grid failures. There is usually a time gap between the power grid failure and the activation of the backup diesel generators, because the diesel generators usually need a short warmup time. To guarantee the safety of the data center during this time gap, the energy storage system, that is also called the Uninterruptible Power System (UPS), is utilized to provide power. The UPS is typically sized to guarantee a 15-minute emergency power delivery for IT equipment of a fully-loaded data center and the critical equipment in the cooling system. The emergency operation of the UPS during the time gap ends once the backup generators are brought online or the power grid recovers. The schematic drawing of a typical data center cooling and electrical system is shown in Figure 9. The fluid flow in the cooling system is denoted by solid lines, and the power flow in the electrical system is denoted by dashed lines.

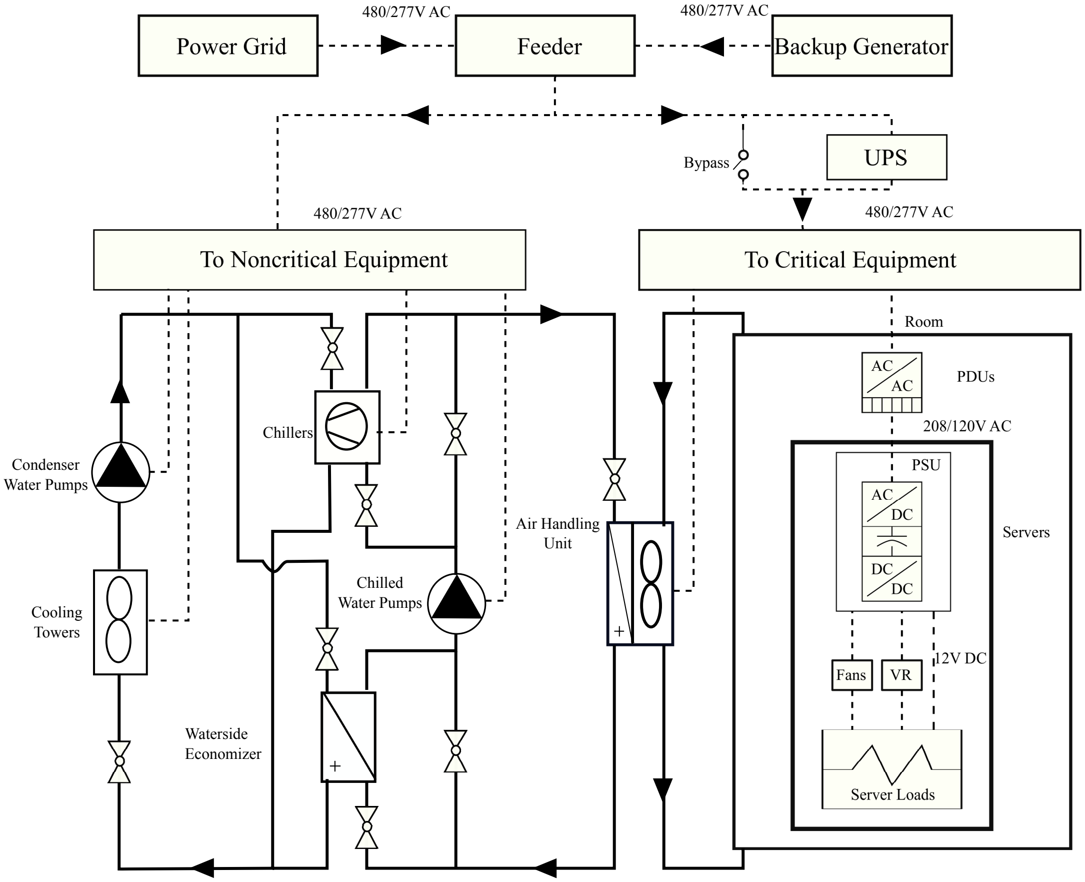


Figure 9. Schematic drawing of the cooling and electrical system in a data center

4.1.1 Cooling System

The studied data center is cooled by a primary-only chilled water system with two identical chillers and one integrated WSE on the load side. The WSE is installed in parallel with chillers on the condenser water side. The design cooling load in the data center is 2,200 kW, which could be satisfied by two identical chillers in the FMC mode or one WSE in the FC mode. The number of variable-speed chilled water pumps, constant-speed condenser water pumps and variable-speed cooling towers are equal to the number of chillers. One CRAH with one supply air fan is designed to deliver cold air to the room. The evaluation of the redundancy for the cooling system such as the backup CRAHs and the redundant piping system is not a purpose of this study, therefore it is not considered here.

The cooling and the control system are modeled using the proposed Modelica package. Dynamics in the cooling system models are represented using two methods: one is lumped volume by specifying the time constant or thermal mass, and the other is signal filter that filters high frequency input signals. For example, the dynamics in the cooling coils are represented by a predefined time constant such as 30s, and the thermal mass of the racks and the servers from [27] are added to the data center room model to calculate the thermal inertia inside the data center room. Furthermore, the dynamic behavior of the motor-driven valves is represented by adding a second-order filter for the input position signals. For the control system, the room temperature is controlled at a set point of 25 °C all the time by adjusting the fan speed in the CRAH. The supply air temperature is maintained at 18 °C by regulating the two-way valve on the waterside of the cooling coils. The chilled water supply temperature is set to be 8 °C under all cooling modes and load conditions.

4.1.2 Electrical System

The configuration of a power distribution system for the data center in North America is represented by the one-line diagram in Figure 9 [28]. Note that in real data centers the electrical architecture has much more complexity and diversity. Based on their importance to keep the data center uninterrupted, all the equipment including IT and cooling equipment in a data center can be categorized into two types: critical and noncritical equipment. Critical equipment are indispensable to keep the data center functioning. A typical design for critical equipment comprehends IT equipment and their supportive supply air fans in the CRAH. Noncritical equipment can be turned off for a short period of time without compromising the safety of the data center. They usually include all the other cooling equipment except CRAH supply air fans.

The data center is connected to the utility service and the backup generators at the building feeder. The incoming power is usually delivered to the data center building by a three-phase 480/277V AC system. During the normal operation, the UPS is bypassed after it is fully charged. The power drawn by noncritical equipment enables the cold chilled water to be produced and delivered to the cooling coils in the CRAH. The supply air fans as critical equipment are powered to enable the heat transfer between the hot room air and the cold chilled water, and thus delivers the cold air to the servers. To supply the servers that usually are DC loads, the 480/277V AC power needs to be first transformed to a lower voltage such as 208/120V in the Power Distribution Units (PDUs). The 208/120V AC power is then converted to 12V DC power through the Power Supply Units (PSUs) in servers. The 12V DC power is finally delivered to the server loads and their auxiliary equipment such as fans. If the server requires power with a voltage less than 12V, then a Voltage Regulator (VR) should be used to decrease the voltage of the DC power. In emergency operation, before the backup generators are brought online, the UPS is only utilized to serve the critical equipment, and no power is delivered to the noncritical equipment.

The electrical system is modeled by the *Buildings.Electrical* package in the Modelica Buildings library. The electrical loads of the cooling equipment are represented by the balanced three-phase AC inductive resistances. The PDUs and PSUs are modeled by connecting existing converter and transformer models as in an actual physical system. The servers are represented as DC loads. The UPS is modeled as a battery storage that does not consider the dynamics of charging and discharging characteristics in this case, and is sized based on the selected critical equipment (IT equipment and supply air fan in the CRAH). The charging and discharging of the battery are controlled by the following logic shown in Figure 10. The state of charge (SOC) of a battery is its available capacity expressed as a percentage of its rated capacity. Knowing the amount of energy left in a battery compared with its full capacity gives the user an indication of how long a battery will continue to perform before it is depleted. As it is not desired to deplete or overcharge the battery, the SOC of the battery should be kept within proper limits. Because the charging and discharging dynamics are not the purpose of this case study, we set the lower and upper bound of the SOC (SOC_l, and SOC_u) as 0 and 1, respectively. When connected to the utility or backup generators, the UPS is charged at a reference rate until being charged to SOC_u. When disconnected, the UPS discharges power to support critical equipment at a discharging rate of the minimum between the required rate $P_{dis,req}$ and the reference rate $P_{dis,ref}$. The potential voltage fluctuation during charging and discharging is not considered in this case.

```
if Connected then
    if $SOC(t) < SOC_u$ then
        $P_{cha}(t) \leftarrow P_{cha,ref}$
    else
        $P_{cha}(t) \leftarrow 0$
    end if
else
    if $SOC(t) < SOC_l$ then
        $P_{dis}(t) \leftarrow 0$
    else
        $P_{dis}(t) \leftarrow min(P_{dis,req}, P_{dis,ref})$
    end if
end if
```

Figure 10. Pseudo codes of UPS charging and discharging control

4.2 Scenario 1: Normal Operation

Energy efficiency of the data center is considered as an important goal during normal operation. Power Utilization Effectiveness (PUE) is used to quantify the energy efficiency as shown in Eq. (9), where the P_{feeder} is the total power that are delivered into the data center for the IT equipment and all their supporting infrastructure, the P_{server} is the power used only by the servers, t_0 and t_1 is the start and the end time for calculating the PUE. The closer the PUE is to 1, the more efficient the data center is.

$$PUE = \frac{\int_{t_0}^{t_1} P_{feeder} dt}{\int_{t_0}^{t_1} P_{server} dt} \tag{9}$$

In this section, we investigate the different energy performances under different part load ratios (PLRs) of the cooling load in the data center room. The considered PLRs are 0.25, 0.50, 0.75 and 1.00, which represents the growing occupancy in the data center. The control settings for the cooling system in all PLRs are the same as the design condition as described in Section 4.1.1.

4.2.1 Simulation Results

Under design cooling load condition (PLR = 1.00), the breakdown of the annual electricity usage of the cooling system is shown in Figure 11. For the chilled water system with WSE, the economizing time, that is the period when the economizers are activated to pre-cool or fully cool the loads, is about 42% of the whole year (Figure 12). Because of the economizing, the fan in the CRAH is the major energy consumer, which takes up about 50.9% of total annual cooling energy. Chillers, pumps and cooling towers utilize 22.8%, 17.1% and 9.2%, respectively.

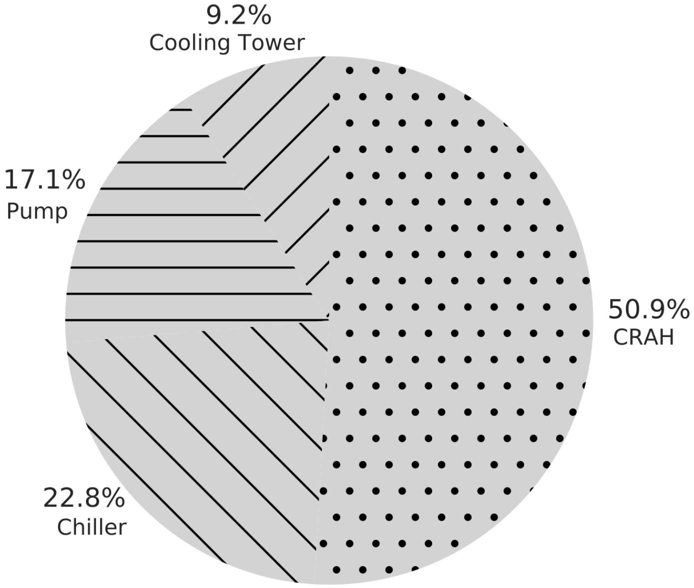
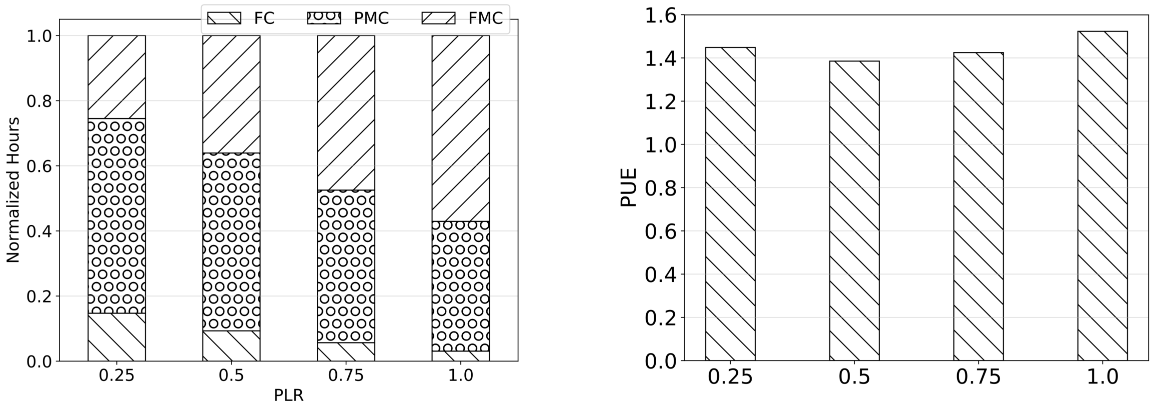


Figure 11. Breakdown of electricity usage of cooling system at PLR = 1.00

Figure 12(a) illustrates the normalized operation time of each cooling mode under different PLRs. As the PLR increases, the hours when the cooling system stays in the FMC mode increase, and that when the cooling system stays in the FC mode decrease. The total hours when the WSE is enabled decreases as the PLR increases. The cooling mode controller described in Section 3.3.1 takes as inputs weather conditions and temperatures in the chilled water loop and the condenser water loop. Although the same weather file is used under different PLRs, the specific temperatures in the water loops are different. For example, the return chilled water temperature at PLR=0.25 is higher than that at PLR=1.00, because the chilled water supply temperature and differential pressure setpoint keep the same in all different cases during this study, and an equal percentage control valve is used on the water side of the CRAH. Thus, condition (5) is easier to be triggered at PLR=0.25 compared with PLR=1.00, which enables the cooling system to operate longer in the FC and the PMC mode at lower PLRs.

Figure 12(b) describes the relationship between PUEs and different PLRs. Among the four PLRs, the lowest PUE is 1.39 at PLR=0.50, and the highest is 1.52 at PLR=1.00, which means the cooling system has a higher efficiency when PLR is not too small or too large. This is determined by the off-design performance curves for each cooling equipment, which is explained as follows in Figure 13.

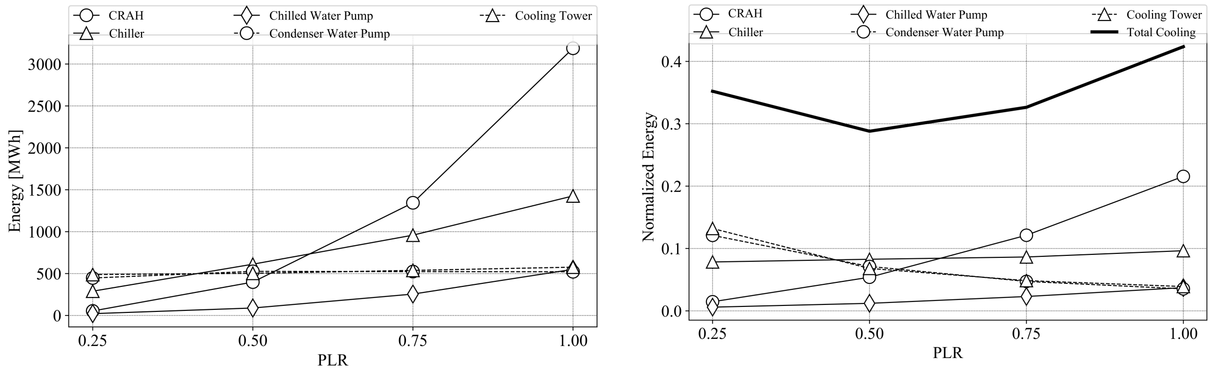


(a) Normalized hours (b) PUE

Figure 12. Operational status at different PLRs

Figure 13(a) shows the detailed energy consumption by each cooling component at different PLRs. The energy usage by the CRAH has an approximately cubic relationship with the PLR. The reason is when the supply and room air temperature control setpoints are not changed as the PLR changes, the speed of the fan in the CRAH is linear to the PLR in the room, and the fan power has a cubic relationship with its speed. Similar profile can be observed in the chilled water pumps. The energy consumption of the chiller has a weak quadratic relationship with the PLR, which is determined by the performance curves of the chillers and the hours of the PMC and FMC modes. Since the condenser water pumps keep constant speed, the energy consumption keeps almost constant at PLR=0.5, 0.75 and 1.00. A difference can be observed between PLR=0.25 and other PLRs, because only one condenser water pump is activated during the FMC mode when PLR is 0.25, while two condenser water pumps are needed at other larger PLRs during the FMC mode. As for the cooling towers, the annual energy increases as the PLR increases, although the relative increase, compared with the fan in the CRAH, is not much. The major reason is that the cooling system runs at the PMC mode during the most time of the year especially when the PLR is low, and the speed of the cooling tower fans at the PMC mode is set to 90% all the time.

Figure 13(b) plots the normalized energy for each cooling component by being divided by the current cooling load. For example, at PLR=1.00, the normalized energy for the CRAH is about 0.22, which means to address 1 kW cooling load, the CRAH fan needs an average of 0.22 kW electricity. The energy efficiency of the cooling tower fans and condenser water pumps increases as the PLR increases, while the opposite trends happen in the CRAH fan, chillers and chilled water pumps. The cooling system efficiency as a whole by combing all the cooling equipment has a highest value at PLR=0.50, where to address 1 kW of cooling load, the cooling system needs about 0.29 kW electricity. Therefore, the lowest PUE happens when the PLR is 0.50 in this case.



(a) Energy consumption (b) Normalized energy consumption

Figure 13. Detailed energy consumption in the cooling equipment

4.3 Scenario 2: Emergency Operation

The priority of emergency operation is to keep the data center safe. Thermally, safety means the heat generated by IT equipment can be removed timely to avoid the temperature of the IT equipment exceeding the maximum safety limit. Operation during emergency situations such as blackout aims to maximize the use of the UPS by only powering critical equipment in order to help IT equipment survive till backup generators are online. Given the capacity of the UPS, the selection of critical and noncritical equipment has significant influence on the survival time. Usually, the more equipment that need to be powered by the UPS during blackout, the shorter the UPS can last. Typically, in a chilled water system with WSE, critical equipment are the IT equipment and the fan in the CRAH. However, there may be opportunities to cool the data center with the UPS by considering some other cooling equipment as critical equipment when the outdoor air is cold enough to activate the WSE. This scenario studies the impact of the selection of critical equipment in a chilled water system with WSE during emergency mode on the thermal and electrical performance in a data center under different cooling load and outdoor conditions.

5.3.1 Scenario Description

The cooling and control system are the same as that in the normal operation. The UPS is designed to last for 15 minutes to power the IT equipment and the fans in the CRAH under the design load condition (PLR=1.00). However, data centers sometimes operate under part load. Therefore, the UPS can have extra capacity after the 15-minute gap. This exposes an opportunity to wisely choose the critical equipment in order to provide a thermally reliable environment even during the gap.

This scenario investigates three options for the selection of critical equipment as listed below. We performed computer simulation to explore the thermal and electrical performances for different outdoor conditions and PLRs. In the models, we assume the power grid fails at 14:00:00, and the generators are not activated until 14:15:00.

Option (a): The IT equipment and fan in the CRAHs are powered by the UPS during the 15-minute gap.

Option (b): The IT equipment and all the cooling equipment other than the chillers are powered by the UPS during the 15-minute gap.

Option (c): When SOC in the UPS is greater than 0.5, then activate Option (b). Otherwise activate Option (a).

5.3.2 Simulation Results

This section compares the thermal and the electrical performances when critical equipment are chosen based on Options (a-c) under different PLRs in different cooling modes. During normal condition, the room temperature is controlled at 25 °C, and the UPS is fully charged (SOC=1). Here we use room temperature to quantify the thermal performance. Too high room temperature in the data center is not desired. And the SOC of the UPS is utilized to metric the electrical performance of different selections of critical equipment. The goal is to see if the UPS can provide enough power for critical equipment, and make the IT thermal environment acceptable.

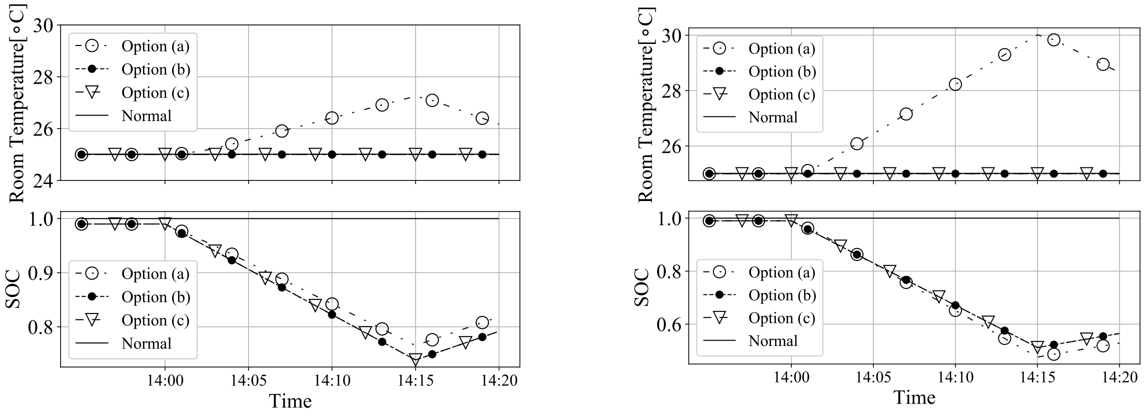
(1) FC mode

The results for FC mode are shown in Figure 14. When the PLR is 0.25, the room temperature has an increase of 2.2 °C at the end of power grid failure by utilizing Option (a). The temperature rise is caused by the deactivation of cooling sources (chillers and economizers). On the contrary, the room temperature can be kept at 25 °C in Options (b) and (c) because the WSE is enabled to cool the room at the cost of more power drawn from the UPS. The SOC after 15 minutes in Option (a) is 0.76, while that in Options (b) and (c) is 0.72. The SOC in Options (b) and (c) is the same because the SOC in this case is greater than 0.5 all the time, which makes Option (c) the same as Option (b). Compared with Option (a), Options (b) and (c) consume less energy in fans, because in the Options (b) and (c), the fan speed is kept at around 0.25, while in Option (a) the fan speed ramps up to around 0.85 in the 15 minutes because the fans need to deliver more air to reduce the room temperature. Although Option (a) requires more fan energy, the increased fan energy is still less than the energy required by the activation of more cooling equipment in Options (b) and (c).

When the PLR is 0.5, because of the lack of cooling sources, Option (a) leads to a room temperature of 30 °C after 15 minutes. In Options (b) and (c), the room temperature can still be controlled at its set point because WSE is able to remove the heat to outdoor air. Although Options (b) and (c) power more equipment, they have higher SOCs after 15 minutes than Option (a), which means the operation during emergency using Options (b) and (c) even consume less energy than Option (a). In Options (b) and (c), the fan speed is maintained at 0.5 as in normal operation, while in Option (a) the fan speed ramps up to 1 during the 15 minutes in order to bring the room temperature down, which consumes more energy at the end.

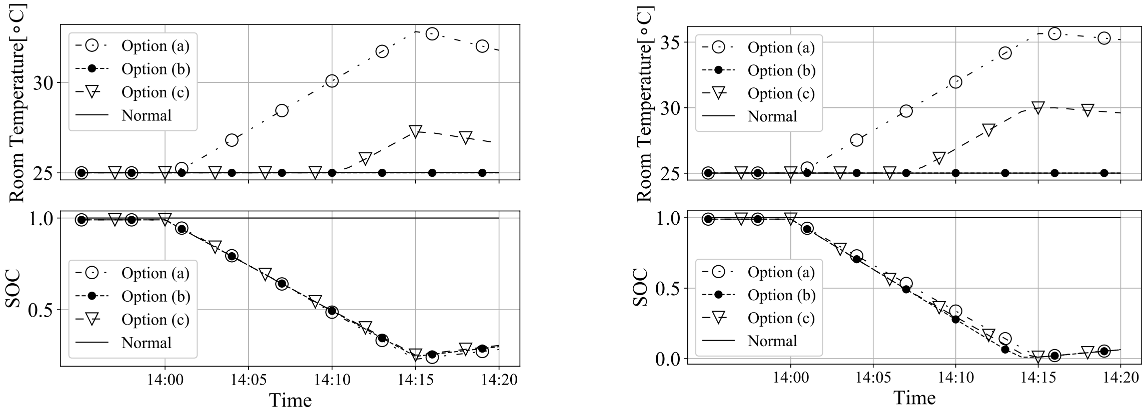
When PLR is 0.75, in Option (a) the room temperature increases to 33 °C at the end of the gap. In Option (b), the room temperature is still maintained at 25 °C. In Option (c), the room temperature is kept at 25 °C before the first 10 minutes when the SOC of UPS is greater than 0.5, and increases to 27 °C at the end of the failure. The fan speed in Option (a) ramps up to 1 during the gap, and that in Option (b) is kept around 0.75 as in normal operation to maintain the room temperature. In Option (c), the fan speed signal keeps at 0.75 at the first 10 minutes. After that, it ramps to 1 at the end of the gap. Option (a) and Option (b) consume almost the same energy during the gap, because the increase of fan power in Option (a) is almost the same as the additional power required by other cooling equipment in Option (b). Option (c) consumes slightly greater power than Option (b) after the first 10 minutes, because the fan needs to run at a higher speed.

When PLR is 1.00, the room temperature in Option (a) reaches about 36 ºC, and the UPS discharges all the power at the end of the gap. For Option (b), the room temperature is kept at 25 ºC, but the UPS can only last about 13.5 minutes, which means the IT equipment has to be shut down for 1.5 minutes until the backup generators are on. For Option (c), the room temperature can be kept at 25 °C when the SOC of the UPS is greater than 0.5. As the UPS continues discharging, the room temperature begins to increase because only the CRAH fan in the cooling system is activated. Similarly, the UPS in Option (c) can only last for 14.5 minutes, which means the IT equipment has to be shut down for about 0.5 minutes. Though Option (b) and Option (c) can keep the data center room at a low temperature when data center is fully loaded, the reliability of the data center room is compromised.



(a) PLR = 0.25

(b) PLR = 0.50



(c) PLR = 0.75

(d) PLR = 1.00

Figure 14. Outage in FC mode

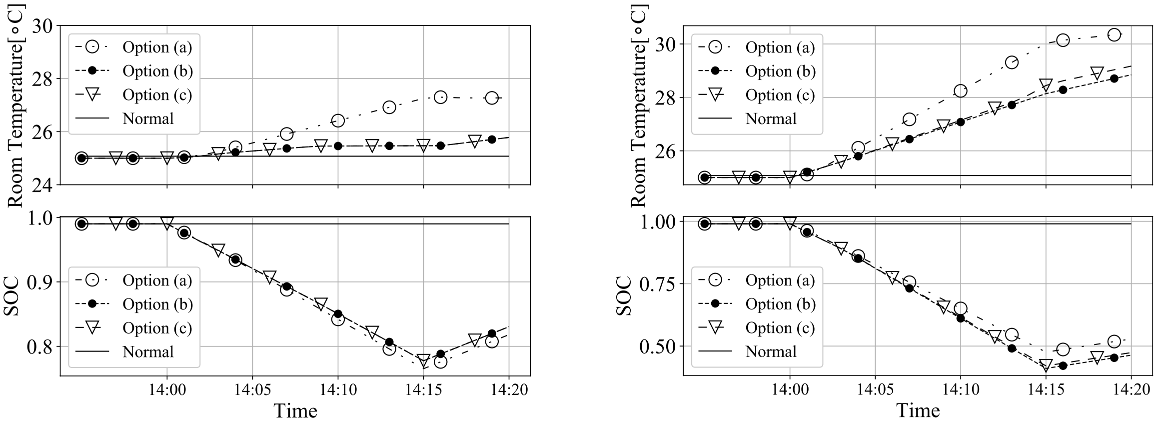
(2) FMC Mode

Figure 15 compares those performances in FMC mode. During FMC mode, the waterside economizer is activated for emergency operation. During the 15 minutes, the outdoor air dry bulb temperature is around 28.5 °C, and the wet bulb temperature is around 19.3 °C. Therefore, the economizer can take some heat out when the condenser water temperature is lower than that in the chilled water loop.

When the PLR is 0.25, in Option (a), the room temperature reaches to 27.2 °C, and the SOC is about 0.76 after the gap. The Options (b) and (c) in this condition are identical because the SOC during the time gap is always greater than 0.5. In Options (b) and (c), the room temperature grows slowly to 25.5 °C at the end of the time gap, and the SOC is about 0.78. The reason that the room temperature cannot be kept at the control point 25 °C as in FC mode is that the cooling source chiller is off, and the outdoor air temperature is too high for the WSE to control the chilled water temperature at 8 °C. For the SOC, Option (a) consumes more energy than Options (b) and (c) during the time gap, although Option (a) needs to power less critical equipment. The error of the PI controller for the data center room air temperature in Option (a) is larger than that in Options (b) and (c), which leads to a faster ramp of CRAH fan speed signal towards full speed in Option (a). Thus, more energy is consumed by the CRAH fan in Option (a) than that in Options (b) and (c).

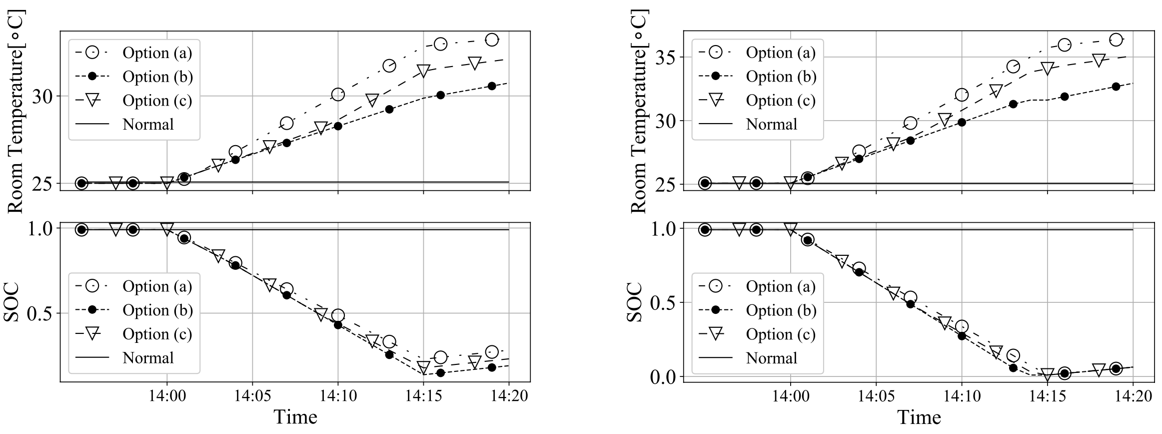
When the PLR is 0.50, and 0.75, Options (b) and (c) have the same performance when SOC is greater than 0.5. As the UPS continues discharging, Option (c) power off the pumps and cooling towers. The room temperature starts to increase faster than that in Option (b). Compared with Option (a), Options (b) and (c) result in a room temperature about 2 °C less at the end of the time gap. Because in all three Options, the CRAH fan speed ramps up to full speed very quickly, and Options (b) and (c) power more critical equipment, they have a lower SOC at the end of the gap than Option (a). However, due to the part loads, the SOC is still larger than SOC_l and the data center can safely pass the gap.

When PLR is 1.00, in Option (a), the UPS discharge all the power at the end of the gap, and the room temperature is as high as 36 °C. Although Options (b) and (c) can reach a lower room temperature, they comprise the reliability of the data center IT equipment because they cannot supply power for 15 minutes. The UPS is depleted at 14:13:30 in Option (b) and 14:14:30 in Option (c). Note that the survival time for FC and PMC mode at PLR=1.00 is the same, because the cooling equipment are working at their full capacities.



(a) PLR = 0.25

(b) PLR = 0.50



(c) PLR = 0.75 (d) PLR = 1.00

Figure 15. Outage in FMC mode

5 Conclusions

This paper presents an open source, equation-based, object-oriented Modelica package for the data center cooling systems. This package includes major cooling component models, control logic, subsystem models and system templates for both chilled water system and direct expansion system, which are designed to support fast modeling. The case study shows that this package is able to perform various analysis, including detailed analysis of energy efficiency and control performance in normal operation, as well as emergency operation by coupling the data center package with electrical package in the Buildings library.

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