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# A Comprehensive Model of Data Center: From CPU to Cooling Tower

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**ABSTRACT** Aiming at addressing environmental challenges, large data centers, such as Facebook, Google, and Yahoo, are increasing share of green power in their daily energy consumption. Such trends drive research into new directions, e.g., sustainable data centers. The research often relies on expressive models that provide sufficient details, however, practical to re-use and expand. There is a lack of available data center models that capture internal operating states of the facility from the CPU to the cooling tower. It is a challenge to develop a model that allows to describe complete data center of any scale including its connection to the grid. This paper proposes such a model building on the existing work. The challenge was to put the pieces of data center together and model behavior of each element so that interdependencies between components and parameters and operating states are captured correctly and in sufficient details. The proposed model was used in the project ''Data center microgrid integration'' and proven to be adequate and important to support such study.

**INDEX TERMS** Data center, model, cooling, server, CRAH, chiller, cooling tower, smart grid, microgrid.

## I. INTRODUCTION

With the increasing expansion of information and communication technologies (ICT), the data center facilities are becoming a sizable part of the energy system. In the period 2007-2012, electrical consumption of data centers had 4% annual growth [1]. In line with the general trend of environment-friendly development, the data centers' owners have interest in providing green services to their customers, including use of renewable energy sources to the greatest extent as possible. The intermittence in renewable energy sources such as solar and wind is a challenge. Data center can use energy storage and electrical grid as a backup for the variability in energy supply. Applying renewable energy sources to a data center drives new and interesting avenues, like the interplay between solar power and free cooling [2], [5].

Data center models in various forms are used in such research studies. DCeET tool [4] showed the effect of climate zones, temperature and humidity on data center energy performance. Through reference model developed using TRNSYS [5], authors showed the effect of the location on operation and associated environmental impact of data center. A three-floor data center building was simulated in the eQUEST software for the evaluation and analysis of free cooling in different climate zones [6]. A dynamic energy model was created using TRNSYS for finding the best cooling configuration for liquid cooled servers, where the excess heat was used for heating a swimming pool [7]. By making complete data center models including predictions of computer workload, available renewable energy, battery state of charge and cost of electricity, a significant reduction in operation cost and $CO_2$ footprint is shown to be feasible [3]. Authors of [8] highlight that while current data center models include workload management, cooling and power supply systems; the direction of development should be towards models that includes storage units, energy leakages, energy transfer costs and power transmission network structure.

The new research agendas require expressive, practical models of data center that allows to see impact throughout the facility. For example, effect of sustainable energy supply on the performance of server rooms (IT task deadlines, capacity, etc.) and operation of cooling equipment and regional power grid.

Often in the literature, models capture only aspects of data center that is of interest for the study: e.g. models of multi-core CPUs; or model of Computer Room Air Handling (CRAH) unit; models of server rooms [11] or IT task scheduling [20]. Some papers describe complete data center from server room to cooling tower [9], [10]. However, those models do not provide enough insights into the data center operating state (e.g. temperatures and air/water-flows) or their descriptions lack details to reproduce the models. Many models are not open and not available for others to use. Some models that are data driven, i.e. some parameters are not calculated, instead supplied by the pre-recorded data from an existing facility. Here interesting dependencies and internal system states can be difficult to capture and observe and, often, such data are simply not openly available.

There is a gap when it comes to available data center models for research. It is a challenge to develop a practical yet detailed complete model of a data center that captures its operation from CPU of the individual servers to cooling tower of the facility. There is need for a model that allows to describe complete facility of any scale including its connection to the power grid.

The paper proposes a coherent model of data center that describes the complete facility: the surrounding power grid, electrical infrastructure, cooling system, server room and individual servers down to CPU. Thermodynamics of various materials and processes is intentionally left out of the model, instead a simplified static model of heat transfer is adopted. The model allows to simulate static operating states of the data center (and states of its components) under various operating conditions. The model is evaluated in microgrid settings with local solar generation and battery.

Such a model will allow to study the impact of user behavior (IT load) and IT infrastructure on internal states of data center facility under various operating conditions (e.g. air-/water-flow, temperatures, power, performance), and on its microgrid and power grid; or impact of grid disturbances on server performance and user satisfaction.

The paper is structured as follows: section II provides an overview of the proposed model, followed by description of the models of server room (III.A) and servers that include single and multi-core CPUs (III.B); the model allows to describe types of jobs that are performed by the server, this affects performance and capacity of the servers (III.C). Section IV describes models of cooling elements CRAH, chiller and heat exchanger and cooling tower. Model of microgrid is briefly described in section V, where also the case study and results of the simulation are presented. Section VI deals with validation of the model. The conclusion provides the final remarks and outlines the future work.

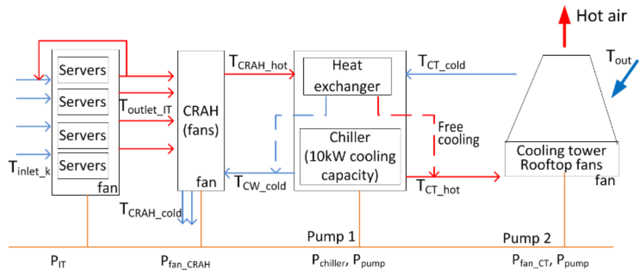


**FIGURE 1. Overview of the data center model.**

## II. OVERVIEW OF THE PROPOSED DATA CENTER MODEL

The model represents a typical data center with a server room and a cooling system. In the server room, servers are arranged into rows of racks; and cooled by CRAH units (Figure 1). The cooling system comprises of CRAH, chiller, cooling tower and pumps that control the water flow.

The model describes behavior of the data center capturing internal states of system components in a simplified practical manner focusing on configuration of servers, power consumption and cooling system.

The motivation of the authors is to create a simplified model of complete facility, and so thermodynamics of various processes (in server, CRAH, chiller and cooling tower) was intentionally avoided.

The model does not account for server rooms with perforated floors and cold- or hot- aisle containment. The available data and capability of the model are summarized in Table 1.

**TABLE 1. Data center model capabilities.**

| The model provides monitoring of the following data: |
|---|
| **Temperatures**: inlet and outlet of individual servers and server rack, CRAH air and water; chiller water on user and source side, cooling tower water and outside temperature |
| **Flows**: airflow in the individual servers, server racks, and CRAH units; water flow in CRAH, chiller and cooling tower |
| **Power consumption**: individual servers, racks, server rooms, CRAH, chiller, cooling tower, fans and pumps; |
| **Cooling system operating states**: overload of CRAH, chiller and cooling tower (capacity, load, remaining heat) |
| **Efficiency and load**: Utilization and coefficient of performance (COP) of the servers and equipment; Power usage effectiveness (PUE) |
| **Server**: task distribution; capacity and frequency |
| **The model allows to capture:** |
| Individual configuration of servers. Racks, CRAH, chiller and cooling tower |
| CRAH arrangements (e.g. Rack Location Unit, RLU, in-row cooling) |
| Failure in the cooling system: CRAH, chiller, cooling towers, fans and pumps |
| Free cooling |
| IT load distribution strategies (including IT load shifting) |
| Weather impact |
| IT job classification |

## III. MODELS WITHIN THE SCOPE OF SERVER ROOM

### A. MODEL OF A SERVER ROOM

The data center that is considered here is on a concrete floor and does not have cold- or hot-aisle containment.

Within a server room typically there are racks of servers and network equipment, cables, cooling units and power distribution units. This model focuses on capturing power consumption and cooling related data of the data center. Therefore, only servers, racks and cooling equipment are considered in the model.

The model can be extended to consider size of the server room, occupancy of the offices; heat produced, and power consumed by the lighting, fire protection and alarm (monitoring) systems.

The considered room has servers that are arranged into racks. Sometimes, the servers are put into enclosures and then into the rack. The model will need to be configured accordingly.

**TABLE 2. Model of the server room.**

| | |
|---|---|
| $P_{server} = P_{idle} + (P_{max} - P_{idle})U\%$ | W |
| $P_{rack} = \sum_{i=1}^{Ns\_r} P_{server},$ | W |
| $f_{air\_server} = 1.78 * \frac{P_{server}}{\Delta T} \cdot 0.000468$, [13] | m³/s |
| $f_{air\_fan\_s} = \frac{f_{air\_server}}{N_F},$ | m³/s |
| $P_{fan\_server\_s} = \frac{f_{air\_fan\_s} \cdot \Delta P\ (Pa)}{\eta},$ | W |
| $P_{fan\_server} = N_F \cdot P_{fan\_server\_s}$ | W |
| $P_{fan\_rack} = \sum_{i=1}^{Ns\_r} P_{fan\_server},$ | W |
| $f_{air\_rack} = \sum_{i=1}^{Ns\_r} (1-k) \cdot f_{air\_server},$ | m³/s |
| $T_{inlet\_k} = T_{CRAH\_cold} + \frac{k \cdot P_{rack}}{f_{air\_rack} \cdot \rho_{air} \cdot c_{air}},$ | ºC |
| $T_{outlet\_server} = \frac{P_{server}}{f_{air\_server} \cdot \rho_{air} \cdot c_{air}} + T_{inlet\_k},$ | ºC |
| $T_{outlet\_rack} = \frac{\sum_{i=1}^{Ns\_r} T_{outlet\_server}}{Ns\_r},$<br>$T_{outlet\_rack} = \frac{\sum_{i=1}^{Ns\_r} T_{outlet\_server} \cdot f_{\mathrm{air\_server}}}{\sum_{i=1}^{Ns\_r} f_{\mathrm{air\_server}}}$ (f1) | ºC |
| $P_{IT} = \sum_{i=1}^{N} P_{rack\_i},\ P_{IT\_CRAH\_i} = \sum_{i=1}^{N_{rack\_per\_CRAH}} P_{rack\_i},$ | W |
| $P_{fan\_IT} = \sum_{i=1}^{N} P_{fan\_rack\_i},$ | W |
| $T_{outlet\_IT} = \frac{\sum_{i=1}^{N_{rack\_per\_CRAH}} T_{outlet\_rack\_i}}{N_{rack\_per\_CRAH}},$<br>$T_{outlet\_\mathrm{IT}} = \frac{\sum_{i=1}^{N_{rack\_per\_CRAH}} T_{outlet\_rack\_i} \cdot f_{\mathrm{air\_rack}}}{\sum_{i=1}^{Nrack\_per\_CRAH} f_{\mathrm{air\_rack}}}$ (f2) | ºC |
| $f_{air\_IT\_CRAH\_i} = \sum_{i=1}^{N_{rack\_per\_CRAH}} f_{air\_rack\_i},$ | m³/s |

The model of the server room is presented in Table 2. The power consumption of the server is assumed to be linearly dependent on the utilization of the server (CPU). The power consumed by the server defines the required airflow [12], [13]. Commonly, there are four fans in a server, hence to calculate its power consumption, the airflow is divided by the number of fans. The power consumption of a fan is found by using impedance and fan performance curves.

In the model, all parameters are taken in metric system. For calculation of airflow, coefficient of 1.78 is taken when temperature is taken in degrees of Celsius (°C), and 3.2 when temperature is in Fahrenheit (F). This will give airflow in CFM (cubic feet per minute). It is then further converted to $m^3/s$ (by *0.000468).

The temperatures in a server room are calculated based on required temperature on the server intake, that is supplied by the CRAH. For instance, recommended by ASHRAE [14] temperature of the room is 22°C. The air is heated when pushed through the server by fans and the resulting temperature depends on power consumed by the server, the created airflow and properties of the air. The model considers the re-circulation that can occur in a rack. The re-circulation index $k$ here denotes the fraction of air that comes from the server exhaust and re-circulates and mixes with the cool room air supplied by CRAH units. $k = 0$ implies no re-circulation, while $k = 0.1$ suggests that 10% of the air is re-circulated. The inlet temperature of the servers then might be higher than 22°C supplied by CRAH.

Typically, CRAH units are positioned to face several rows of racks. In this model, we consider the load of each CRAH unit as a number of racks that the CRAH unit is supposed to cool (circulate the cold air around). Similarly, in-row cooling [10], [15] can be modelled by assigning the number of racks per CRAH unit. Alternatively, the cooling load of each CRAH can be calculated evenly by dividing the total server power in the room by the number of CRAH units. However, with our approach the variable heat density of the server room can be considered. This is known as RLU (rack location unit) proposed by Sun Microsystems [16], [17]. Each rack location can have servers with various performance and tailored power supply and cooling.

The averaging algorithm used for computing $T_{outlet\_IT}$ and $T_{outlet\_rack}$ is simplified and assumes equal flow of each component ($f_{air\_server}$). More realistic approach is to average on the enthalpy of the components. In this paper, where the specific heat of air and water are constant ($c_{air}$, $c_{water}$), so the method can be simplified to flow rate weighted average (f1), (f2) (and for $T_{CRAH\_hot}$ (f3) in Table 6).

### B. MODEL OF THE SERVER

Since it is challenging to calculate power consumption of a server directly from the CPU frequency, as it also depends on the voltage and other parameters (1) [18], [19], the power consumption of a server at various frequencies will be calculated indirectly, relative to the power consumption at max $f$ (given) and current utilization (load) of the CPU (2).

The total power can be split into dynamic ($P_{transition}$ and $P_{short\_circuit}$) and static. $P_{transition}$ is due to current for charging and discharging the load capacitance ($C$) formed by switching node from low to high state and vice versa ($f$). $P_{short\ circuit}$ results from short circuit current flowing during the dynamic switching activities, due to non-zero rise and fall times of the control signal. $P_{static}$ is due to the transistors leakage currents.

$$P_{server} = P_{static} + P_{short\ circuit} + P_{transition}$$
$$= mV + \alpha \mathrm{E}_{short\ circuit} f + \alpha \frac{1}{2} C V^2 f \quad (1)$$
$$P_{server} = P_{idle} + (P_{max} - P_{idle}) \frac{U(\%)}{100}, \quad (2)$$

where $V$ is the operating voltage, $\alpha$ – a number of transitions per clock cycle (activity factor), $m$ – a constant that captures number of transistors, design parameter and leakage current, $E_{short\ circuit}$ – power of a single short-circuit.

The proposed model of a server considers the resources that are available at the server. The resources that are used for processing IT jobs are processing cores, RAM, disk space and bandwidth. The machines can be categorized into various configurations based on number of cores and CPU frequency. Such categorization allows simulation of the task distribution across the servers. More powerful machines can perform more tasks and faster, however consuming larger amount of power than the less powerful and slower machines. The proposed model allows to see the resulting power consumption of various task distribution strategies. In this model, memory usage is not considered at this stage, however intensive usage of memory can affect the power consumption of the server.

The servers in the model have 3 power states, though it can be customized to any number of states as per data sheet for a given CPU. P0 is often the highest performance state. P1 and P$n$ are successively lower-performance states. In states P1-P$n$, voltage and frequency are scaled.

There are potential power savings of dynamic voltage and frequency scaling (DVFS). According to [12], in 2.4GHz system, savings are possible when CPU load is less than 2/3 of peak by dropping the frequency to 1.8GHz. Further 10% savings is achievable when utilization drops to 1/3 by going to the frequency of 1 GHz. Further decline in the load (<10%) the gains of dynamic voltage and frequency scaling are back to about 10% due to lack of proportionality in the system level.

Table 3 presents the basic structure of the server model, that is used to model single core machines with or without frequency scaling. These models are extended to model multi-core CPU servers with or without frequency scaling; with un-/even task distribution across the cores. These are implemented in the proposed model.

The power consumption of each core is calculated in the same way as for the single core server, only the utilization is considered for each core. If even task distribution is implemented, then all cores will have the same utilization.

$$\text{core tasks} = \text{current\_tasks/N\_cores}.$$

In the case of uneven task distribution, cores are loaded to the maximum first before loading the next core (Table 4). So, the server can have one core loaded to 100% and other to 25% and rest are in the idle state.

The capacity of the server and utilization can be given in percentages (%). In this model the capacity and load are calculated based on the tasks performed by the server. This method is described below.

### C. JOB CLASSIFICATION

It is useful to consider job classification when studying impact of various task distribution methods on power consumption of the server. The size of the jobs and tasks, and their type will affect how much the server is loaded and for how long and therefore its consumption of power and energy. There are two types of jobs: batch jobs and service jobs [20]. Batch jobs are of a shorter duration (from minutes to hours). Service jobs consume resources over an extended period of time and have a priority over the batch jobs. Jobs are broken down into tasks, which is a smallest unit that are processed on the server. Jobs arrive at a particular rate and broken down to the tasks that are allocated to the servers.

In this model, the capacity of the server (CPU frequency) and utilization are calculated based on type and the size of jobs and the tasks. Below is an example of task definition, which is based on [21]. User of the model can define other size and type of the task that is more fit to the problem at hand.

Suppose that a task takes $5 \cdot 10^5$ instructions to execute. Out of these instructions 50% execute in 3 clock cycles; 30% in 4 clock cycles and 20% in 5 clock cycles. Hence, the execution

**TABLE 3. Model of the server.**

| | |
|---|---|
| capacity $= \frac{f}{3.7*X}$, X – number of instructions in the single task | Tasks/second |
| current_tasks = tasks (assigned to the server) | tasks |
| idle_tasks = capacity – current_tasks | tasks |
| $U = 100 - \frac{idle\_tasks \cdot 100}{capacity}$, | % |
| $P_{server} = P_{idle} + (P_{max} - P_{idle}) \cdot \frac{U}{100}$, | W |
| If ((35 <$U$) AND ($U$<65)) then | |
| capacity1 $= \frac{f1}{3.7*X}$, | Tasks/second |
| idle_tasks = capacity1 – current_tasks | tasks |
| $U1 = 100 - \frac{idle\_tasks \cdot 100}{capacity1}$, $U = U1$; | % |
| Pserver = 0.9 · Pserver | W |
| Else if ($U$<36) then | |
| Capacity2 $= \frac{f2}{3.7*X}$, | Tasks/second |
| idle_tasks = capacity2 – current_tasks | tasks |
| $U2 = 100 - \frac{idle\_tasks \cdot 100}{capacity2}$, $U = U2$; | % |
| If ($U$<10) then | |
| Pserver = 0.9 · Pserver | W |
| Else Pserver = 0.81 · Pserver | W |
| End if | |
| End if | |

**TABLE 4. Multi-core server with un-even task distribution.**

| | |
|---|---|
| W=fix(current_tasks/core_capacity) | number of fully loaded cores |
| F= (current_tasks/core_capacity) | utilization of the partially loaded core |
| PcW = W · Pcore_max | power consumption of the fully loaded cores |
| PcF = Pcore_max · F | power consumption of the partially loaded core |
| Pserver = Pidle + PcW + PcF | power consumption of the server |

time for a task is (3).

$$T_{exec} = \frac{1}{f} \cdot 3.7 \cdot X, \tag{3}$$

where $f$ is the clock frequency of a core (CPU) and $X$ is the number of instructions in a task.

Then, the speed of the core (server) in terms of tasks can be expressed as (4).

$$Speed_{tasks} = \frac{f}{3.7 \cdot X} \text{ tasks/second} \tag{4}$$

Capacity of the core (CPU, server) in terms of tasks can be then expressed as (5).

$$Capacity_{tasks} = \frac{f}{3.7 \cdot X} \text{ tasks/second} \tag{5}$$

Then, the jobs that are arriving at the data center, can be categorized in to 8 classes (Table 5), similar to [20].

**TABLE 5. IT job classification.**

| Class | Job (tasks) | Class | Job (tasks) |
|---|---|---|---|
| 1 | $38{,}8\cdot10^4$ | 5 | $79.48\cdot10^4$ |
| 2 | $149.6\cdot10^4$ | 6 | $9.35\cdot10^4$ |
| 3 | $303.89\cdot10^4$ | 7 | $32.7\cdot10^4$ |
| 4 | $196.36\cdot10^4$ | 8 | $23.37\cdot10^4$ |

This job and task modeling and categorization is customizable or can be completely omitted in in the model. The utilization of the server then can be set as percentage (e.g. 20%), where 100% is a fully loaded server.

The model can include the job generator to simulate arrival of the jobs to the data center. The generator should output jobs at the defined job arrival rate $\lambda$, that belongs to one of the classes above and have assigned deadlines. The user can define the probability $p_{class}$ of a job belonging to a particular class. Then jobs with given arrival rate and class are broken down to the tasks. These tasks are characterized either in the similar manner as described above or in other way. These tasks then can be distributed to the machines.

## IV. MODEL OF THE COOLING SYSTEM

### A. MODEL OF CRAH UNIT

The CRAH unit considered in this model can be configured with the datasheet for a particular CRAH equipment.

The input to this model is temperature of the server outlet, required cold air temperature of the server room, temperature of the incoming cold water (or liquid) from the chiller, cooling load of the CRAH unit. Cooling load of the CRAH unit is the heat generated by the servers, that is the power consumed by the servers. The calculation of the cooling load of CRAH is described in section III. The re-circulation of the hot air is considered, if no re-circulation $k = 0$.

From the datasheet of the CRAH unit, the following is required: performance curve (*heat load* vs *water flow* (and, if given, *range*)), air flow ($f_{air\_IT\_CRAH\_i}$) and fan efficiency and pressure drop. The latter two can also be taken from the ASHRAE recommendations.

First the water flow required to remove the heat is calculated. If the heat load is within the nominal capacity of the CRAH unit, then all heat is removed with the corresponding water flow. This can be found from the performance curve of the CRAH, or other relevant data defined in the data sheet. The temperature of cold air $T_{CRAH\_cold}$ (Figure 1) is calculated based on the outlet temperature of the server and reflects how much heat the CRAH unit can remove given the *range* (the difference between the cold water coming from the chiller and hot water returned by the CRAH unit). The range will impact how much heat can be removed and the water flow.

If the heat load exceeds the nominal capacity of the CRAH unit, not all heat is removed. The remaining heat stays with the air, implying that the $T_{CRAH\_cold}$ will be warmer than required (22°C).

Once the heat that has been removed is known ($Q_{CRAH\_calc}$), the temperature of the return warm water can be calculated ($T_{CRAH\_hot}$). The incoming hot air from servers are cooled by heating the cold water coming from chiller. $T_{CRAH\_hot}$ is then derived from $T_{CRAH\_cold}$ based on the water flow and heat are calculated above in previous step.

This model includes $h$ is an excess heat removal index. This parameter comes into play when the heat load exceeds the nominal capacity of the CRAH. The excess heat ($Q_{remain}$) is not being removed, it remains in the incoming air (or liquid). If $h = 0$, the CRAH only removes the nominal amount of heat and rest of the heat remains in the incoming air. In case of possible failure, and when incoming liquid (air) is much hotter than the nominal value, the refrigerant can be heated to higher than nominal value and, therefore, take a portion of excess heat ($h \cdot Q_{remain}$). This case is modelled by setting $h$ to percentage of the excess heat that would be transferred to the refrigerant by heating it. For example, if $h = 0.1$, then 10% of the excess heat (that is what remains after the nominal amount of heat is removed), is spent to heat the water. This impacts the temperature of the water that is returned by CRAH to the chiller and the cold air supplied by CRAH. This allows to model failures of CRAH and chiller.

If the water from the chiller brings heat load (indicated by the temperature) that is higher than nominal (expected) ($range = 0$), the CRAH unit will operate outside of its operating limits. In such a case, the CRAH unit is not able to cool the incoming air.

The aggregated water flow of all CRAH units constitutes the incoming water flow to the chiller. The temperature of the aggregated water from CRAH units is the average of water temperatures from each CRAH.

In this model power consumed by the CRAH is calculated based on COP, however, if the data for fans are known, it can be calculated as (6).

$$P(fan) = \frac{f_{airflow} \cdot \Delta P(Pa)}{\eta}, \tag{6}$$

where P(Pa) is the pressure drop and $\eta$ is the efficiency.

**TABLE 6.** Model of the CRAH.

| | |
|---|---|
| $Q_{CRAH\ i} = (1-k) \cdot P_{IT\ CRAH\ i}$ | W |
| $range = T_{CRAH\ hot} - T_{CW\ cold}$ | °C |
| *waterFlowTempCalc(in:range; out:* $T_{CRAH\ Cold}, f_{water}, Q_{CRAH\ calc}$*);* | |
| $T_{CRAH\_hot\_i} = T_{CW\_cold} + \frac{Q_{CRAH\_calc}}{\rho_w \cdot c_w \cdot f_{water}}$, | °C |
| If (range <=0) then | |
| CRAH is out of operating limits. | |
| $T_{CRAH\ hot} = T_{CW\ cold}$ | °C |
| End if | |
| $f_{water\ CRAH\ i} = f_{water}$ | $m^3/s$ |
| $T_{CRAH\_hot} = \frac{\sum_{i=1}^{C} T_{CRAH\_hot\_i}}{C}$ (C – number of CRAH units), $T_{CRAH\_hot} = \frac{\sum_{i=1}^{C} T_{CRAH\_hot\_i} \cdot f_{water\_CRAH\_i}}{\sum_{i=1}^{C} f_{water\_CRAH\_i}}$,(f3) (see section III.A) | °C |
| $COP = \frac{T_{CRAH\_cold}}{T_{outlet\_IT} - T_{CRAH\_cold}}$, $P_{CRAH\_i} = \frac{Q_{CRAH\_calc}}{COP}$, | W |
| $f_{water\ CRAH\ total} = \sum_{i=1}^{C} f_{water\ i}$, | $m^3/s$ |
| $P_{CRAH} = \sum_{i=1}^{C} P_{CRAH\ i}$, $Q_{CRAH} = \sum_{i=1}^{C} Q_{CRAH\ calc\ i}$, | W |
| Function: *waterFlowTempCalc(in: range; out:* $T_{CRAH\_Cold}, f_{water}, Q_{CRAH\ calc}$*);* | |
| If ($Q_{CRAH\ i} > Q(range, f_{max})$) then | |
| $Q_{remain} = Q_{CRAH\ i} - Q(range, fmax)$ | W |
| $T_{CRAH\_cold} = T_{OUTLET\_IT} - \frac{(h*Q_{remain}) + Q(range, fmax)}{\rho_{air} \cdot c_{air} \cdot f_{air_{CRAH_i}}}$. | °C |
| $f_{water} = f_{max}$ | $m^3/s$ |
| $Q_{CRAH\ calc} = Q(range, f_{max}) + h \cdot Q_{remain}$ | W |
| Else if ($Q_{CRAH\ i} <= Q(range, f_{max})$) | |
| $f_{water} = f(Q, range)$ | $m^3/s$ |
| $T_{CRAH\_cold} = T_{OUTLET\_IT} - \frac{Q\_CRAH\_i}{\rho_{air} \cdot c_{air} \cdot f_{air\_crah}}$; | °C |
| $Q_{CRAH\ calc} = Q_{CRAH\ i}$; | W |
| End if | |

The aggregated heat that has been removed by the CRAH units ($Q_{CRAH\_calc}$) is the heat load of the chiller ($Q_{evap}$).

### B. MODEL OF THE CHILLER AND HEAT EXCHANGER

The model of the chiller requires to be configured with the data from datasheet of the selected chiller. Data that is required are the operating limits of the chiller ($T_{CT\_hot\_limit}$, $T_{CW\_cold\_limit}$), water flow, pumps' efficiency and pressure drops.

The input to the model is temperature of the hot water coming from CRAH, required temperature of the cold water supplied to CRAH, aggregated water from required by CRAH, and the heat transfer coefficient *h*.

The first step is to calculate the temperature of the chilled water that is supplied to CRAH units. The hot water $T_{CRAH\_hot}$ is cooled down by warming up the cold water coming from cooling tower $T_{CT\_cold}$ to the temperature $T_{CT\_hot}$. The heat is removed from the CRAH side and added to the cooling tower (CT) side.

If the heat load is within the nominal capacity of the chiller, then the calculation is straightforward. In the alternative case, only nominal amount of heat is removed from the hot water returned by CRAH units. The rest of the heat remains with the incoming water. If *h* is considered, then a fraction of the remaining heat will be transferred to heat the water coming from CT.

**TABLE 7.** Model of the chiller.

| | |
|---|---|
| $Q_{evap} = Q_{CRAH}$ | W |
| If ($Q_{evap} <= Q_{nom}$) then | |
| $T_{CW\_cold} = T_{CRAH\_hot} - \frac{Q_{evap}}{\rho_w * c_w * f_{water\_CRAH\_total}}$, | °C |
| $Q_{temp} = Q_{evap}$ | W |
| Else if ($Q_{evap} > Q_{nom}$) then | |
| $Q_{remain} = Q_{evap} - Q_{nom}$ | W |
| $T_{CW\_cold} = T_{CRAH\_hot} - \frac{Q_{nom} + (h*Q_{remain})}{\rho_w * c_w * f_{water\_CRAH\_total}}$, | °C |
| $Q_{temp} = Q_{nom} + (h*Q_{remain})$ | W |
| End if | |
| If (($T_{CW\_cold} - T_{out}$)>3) and ($T_{CW\_cold} <= T_{CW\_cold\_limit}$) then (free cooling) | |
| $P_{chiller} = 0$; | W |
| Else if (not free cooling) then | |
| $COP = \frac{T_{CW\_cold}}{T_{CRAH\_hot} - T_{CW\_cold}}$, | |
| $P_{chiller} = \frac{Q_{temp}}{COP}$, | W |
| End if | |
| $Q_{CT} = Q_{temp} + P_{chiller}$ | W |
| $T_{CT\_hot} = T_{CT\_cold} + \frac{Q_{CT}}{\rho_w \cdot c_w \cdot f_{water\_tower}}$, | °C |
| If ($T_{CW\_cold} > T_{CW\_cold\_limit}$) OR ($T_{CT\_hot} > T_{CT\_hot\_limit}$) then | |
| Chiller is out of operating limits! | |
| End if | |
| $P_{pump_1} = \frac{f_{water_{CRAH_{total}}} \cdot \Delta P_{pump1}}{\eta_{pump1}}$, $P_{pump\_2} = \frac{f_{water\_tower} \cdot \Delta P_{pump2}}{\eta_{pump2}}$, | W |
| $P_{pump} = P_{pump\_1} + P_{pump\_2}$, | W |

If *free cooling* is possible, then the chiller is not used, otherwise the chiller power consumption is calculated based on the COP. The power consumed by the chiller is assumed to be dissipated as heat, which adds to the cooling load that is to be removed by CT.

The cooling load ($Q_{CT}$) on to the CT is calculated as a sum of the heat removed by the chiller and the heat generated by the chiller.

The cool water coming from cooling tower is heated in the chilling process and the resulting temperature depends on cooling load to be removed, water flow at CT side and characteristics of the water (of the cooling liquid used).

The model will warn if the chiller starts operating outside the recommended operating limits. However, it will not stop, and parameters will continue to be calculated as described above, even if they will exceed the allowed limits.

### C. MODEL OF THE COOLING TOWER

The model of the cooling tower (CT) is based on the recommended practices by ASHRAE [22] (Table 8). The model can be customized to fit selected CT.

The CT characterized by the *range* and approach temperature ($T_{approach}$) [22]. Range is the difference between the water entering ($T_{CT\_hot}$) and leaving the CT ($T_{CT\_cold}$).

**TABLE 8. Model of cooling tower.**

| | |
|---|---|
| $\lambda_{CT} = \frac{f_{water\_tower}}{f_{water\ tower\ nom}}$, | |
| range = $T_{CT\_hot} - T_{CT\_cold}$ | °F |
| If (range < 3) then – in Fahrenheit | |
| T_CT_hot is too cold - out of operating limits. | |
| Take range as 4 (min) | |
| End_if | |
| If (range > 30) in Fahrenheit | |
| Take T_CT_cold as for max range (range = 30) | |
| The T_CT_hot is too hot – out of operating limits. | |
| End if | |
| $T_{CT\_cold} = f(T_{out}, range, \lambda_{CT})$ | °C |
| $COP = \frac{T_{CT\_cold}}{T_{CT\_hot} - T_{CT\_cold}}$, $P_{CT} = \frac{q_{CT}}{COP}$ | W |

The approach is the difference between the leaving water temperature ($T_{CT\_cold}$) and the outside air temperature ($T_{out}$) and usually within 2.8°C $< T_{approach} <$ 4°C. The load of a CT ($\lambda_{CT}$) here is defined as a relation between water flow required by the chiller to remove the heat and the nominal water flow of the CT.

The $T_{CT\_cold}$ depends on outside temperature, range and load of the CT (Figure 2).

The model will warn if the hot water returning from chiller ($T_{CT\_hot}$) is too cold (in this case the range is taken as minimum 4 °F), or the water ($T_{CT\_hot}$) is too hot, in which case the range is taken as maximum 30 °F).

The power consumption of the CT can be calculated based on the fan characteristics (if known) or on COP.

The CT completes the model of the data center. The total power consumption of the data center can be calculated as in (7).

$$P_{total} = P_{IT} + P_{fan\_IT} + P_{CRAH} + P_{chiller} + P_{CT} + P_{pumps} \tag{7}$$

The next section will present a case study to demonstrate the model in the selected configuration of the data center.

## V. CASE STUDY, SIMULATION AND RESULTS

### A. SELECTED CONFIGURATION OF THE DATA CENTER

The proposed model of the data center was applied within the project *Data center Microgrid Integration* (DMI) [23]. This project studies the feasibility and potential of the data center as a self-contained self-reliant unit. Data center is an operator of its microgrid, that comprises of renewable generation (solar), energy storage (battery), water tank storage for cooling and have a backup connection to the main grid.

Data center primarily relies on solar power and battery to cover its own power demand, and so schedules the IT load accordingly. IT load is often not a flexible parameter, and data center must schedule it according to the deadlines. Data center might need power when it is not available from solar source or storage; and will need to buy it from main grid, regardless of the price. This can be balanced, by selling

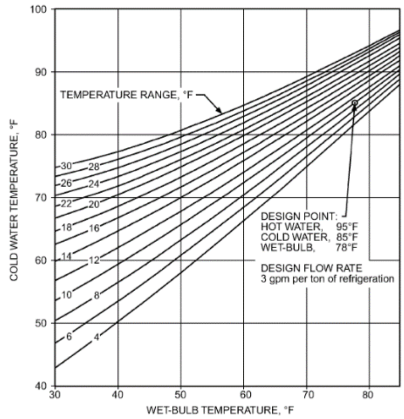


**FIGURE 2. Cooling tower performance - 100% design flow [22].**

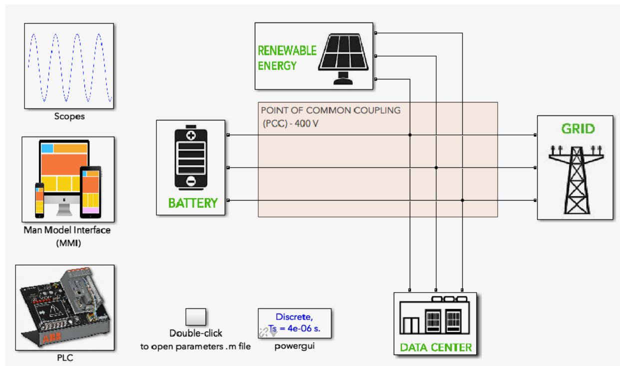


**FIGURE 3. DMI data center microgrid model (Matlab Simulink).**

renewable energy back to the grid or providing ancillary services with the energy storage or with islanding from the grid. Thus, data center microgrid can participate in demand response programs.

To study the feasibility, benefits and drawbacks of such an approach, a detailed model is required, that allows to see impact on power consumption of data center and its components, operating states of the cooling system as the IT load is shifted around in space and time; simulate failures of various cooling and energy storage equipment; and simulate data center operation in the microgrid settings. The proposed model is a good fit for such study.

The model of microgrid was developed to support the study (Figure 3). The microgrid contains: the regional power grid, the energy storage (battery, 30kWh), solar generation (10kW), the data center (10kW), two inverters, control and HMI panels. The challenge was to achieve acceptable power characteristics of the microgrid and develop a reversible AC-DC inverter model. The developed microgrid can operate in grid connected and islanded modes.

The reversible AC-DC converter is used in both interfaces for battery and solar power source. Figure 4 shows the power electronics part of the interface:

- DC voltage source, here managed by a battery but could be managed by a photovoltaic source;

**TABLE 9.** Selected data center configuration.

| Server room configuration | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Number of servers | Number of racks | Number of CRAH units | ΔT (server) | k | P idle, server room | P max, server room | T outlet (server) | Type of server | Number of fans in a server |
| 36 | 2 | 4 | 12°C | 0 | 5 kW | 10 kW | 34°C | Facebook Open Compute | 4 |
| CRAH unit, chiller and cooling tower configuration | | | | | | | | | |
| $T_{CW\_cold}$ | CRAH capacity | Chiller capacity | $T_{out}$ | $T_{CT\_cold}$ | $T_{CT\_hot}$ | Chiller water flow (condenser) | Cooling tower capacity | Cooling tower characteristics by ASHRAE guideline [22] | |
| 15°C | 3.1 kW | 12.9 kW | 20°C | 35°C | 40°C | 0.79 l/s | 13.6 kW | $T_{CT\_cold}$ vs $T_{out}$ | |

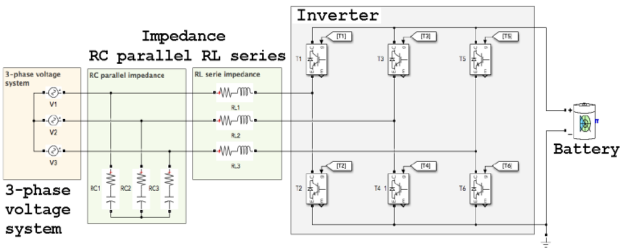


**FIGURE 4.** 3-phase power electronics structure.

- inverter composed of 3-arm and each arm is composed of 2-transistor with a diode placed in anti-parallel;
- LC impedance which takes the role of low-pass filter;
- 3-phase voltage system.

The inductance was sized to limit the current waves. Capacitor is sized to form a low-pass filter to provide almost perfect sine-wave to the data center when the grid is disconnected.

Two control modes have been modelled. The first one is current regulator which allows to control the value and the direction of the active and reactive power (needed to charge the battery and implement the droop-control regulation). The second control mode is voltage regulator that maintains a steady voltage level to the load in islanded-mode. A model allows to switch between these modes (current/voltage) depending on whether grid is connected or not. In the grid connected case both DC power sources are controlled in current regulation mode. If grid is disconnected and solar power is available, then battery is in droop control and PV is in voltage regulation mode; otherwise battery is in voltage regulation mode.

The battery management (state of charge, SoC) is implemented using Matlab function blocks.

Data center is modeled in Matlab Simulink straightforward as described above (equations in the tables), capturing servers, server rooms, CRAH units, chiller and cooling tower in separate modules using Simulink native blocks.

Selected configuration of the data center is detailed in Table 9. The following air and water properties are considered in the model [24], [25]: air density ($\rho$) 1.18 kg/m$^3$ at 25°C; heat capacity of air ($c$) 1010 J/(kg °C); water density 998.68 kg/m$^3$ at 20°C; water heat capacity 4187 J/(kg °C).

**TABLE 10.** Selected DMI server configuration for the simulation.

| Frequency, Hz | Power states, Hz | | $P_{idle}$, W | $P_{max}$, W | N cores | Frequency scaling |
|---|---|---|---|---|---|---|
| | P1 | P2 | | | | |
| 2.4 * $10^9$ | 1.8·$10^9$ | 1·$10^9$ | 138.8. | 277.7 | 6 | no |

The server configuration is selected as described in Table 10.

### B. SIMULATION AND RESULTS

The microgrid is simulated in both grid connected and islanded mode. The operation of the microgrid is controlled by a programmable logic controller (PLC) (Figure 3). Data center, through the PLC, controls the battery and manages operation in both modes. The weather data are provided to the solar generation. Microgrid also monitors its own frequency and can detect overload/underload conditions.

In grid connected mode, the voltage level and the frequency are imposed by the grid. In that case, both inverters (battery and solar panels) are current controlled. In the scenario in Figure 5 battery is charging while solar panel generates power.

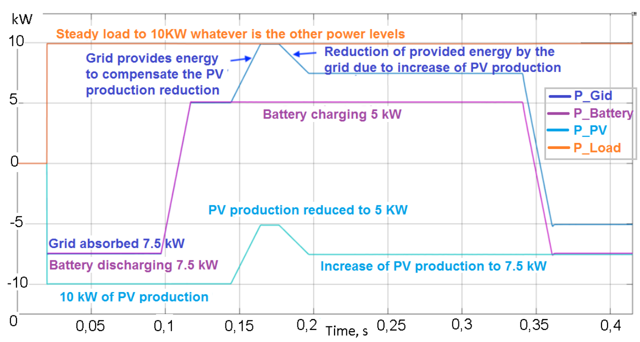


**FIGURE 5.** Active power flow in grid connected mode.

In islanded mode, the frequency and the voltage level are regulated by the inverter. Indeed, when both battery and photovoltaic source are producing energy, the inverter of the battery regulates the frequency level and voltage level through the droop-control method (Figure 6).

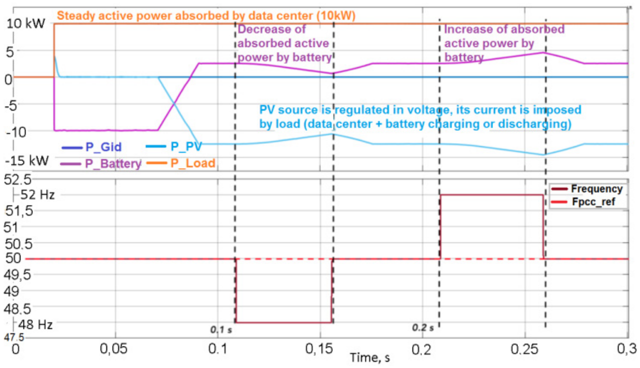


**FIGURE 6.** Active power in islanded mode with droop control.

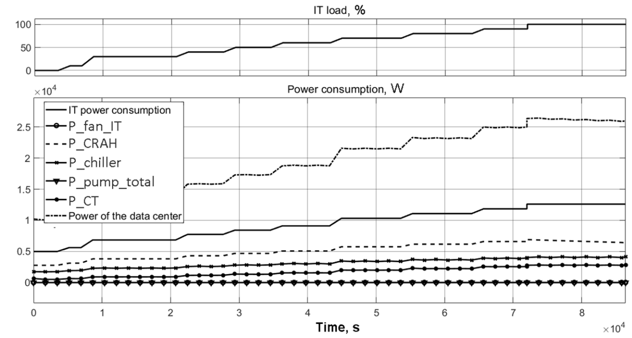


**FIGURE 8.** Data center with 6-core servers: power consumption of the components.

Below, the results are presented for one configuration of the data center (Table 10). This is due to page limitation of the paper and it is sufficient to demonstrate main capabilities of the model.

In the simulation, the utilization (IT load) of the server is steadily increased from idle to 100%. To demonstrate overload of CRAH units, capacity of the servers was increased from 10 kW to 12.6 kW (Table 9). CRAH capacity 3.1 kW, while one rack is 6.3 kW, and one rack is shared between two CRAH, so each CRAH has 3.15 kW cooling load. Which means 50 W of heat remains within outgoing cold air $T_{CRAH\_cold}$.

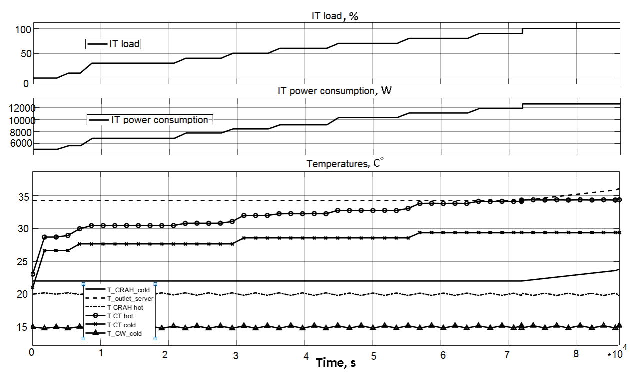


**FIGURE 7.** Data center with 6-core servers (without frequency scaling): temperatures server room and cooling system.

Figure 7 shows temperatures within data center. CRAH maintains $T_{CRAH\_cold}$ at desired 22 °C. Once IT load heats 100% and IT power consumption reaches 12.6kW, $T_{CRAH\_cold}$ and $T_{CRAH\_hot}$ start growing and reach to 36°C (from 24°C). This increase corresponds to excess heat of 50W (remaining heat). The rest of temperatures are stable; cooling tower temperatures grow as load on cooling tower increases, since there is no free cooling (P chiller adding just under 5 kW).

Figure 8 shows power consumption of the data center and its components. Power follows the trend of the IT power consumption that is increasing with the IT load. The pump power consumption remains constant. Calculations of power consumption can be improved (e.g. for CRAH and cooling tower), if information on fans was available. The total power consumption reaches about 25 kW, 12.6 kW of which is for IT (servers). It is possible to calculate and plot the energy consumption, as the model is simulated for 24 hours.

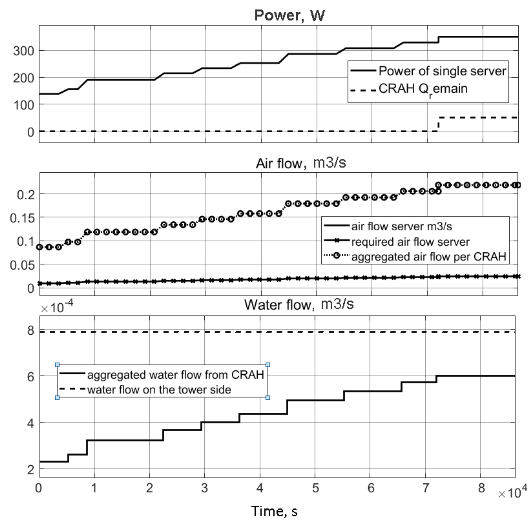


**FIGURE 9.** Data center model: air and water flows.

Figure 9 shows the air and water flows in the data center. Server fans match the required airflow of the server as IT load increases. CRAH increases the water flow to keep up with the growing temperature $T_{outlet\_IT}$ as IT load increases. However, it reaches the maximum flow of 0.0006 $m^3$/s when cooling load exceeds the capacity (50W); and hence not able to remove all heat. As a result, the $T_{CRAH\_cold}$ increases as seen in Figure 6. The water flow on the tower side remains steady as the chiller does not exceeds it cooling capacity and $h = 0$.

It is possible to simulate overheating of water in CRAH and chiller, overloading the cooling system and vary $k$ and $h$. One can simulate various configurations of the servers (single core, multi-core, with/without DVFS, variable core loads) and monitor state of the system (data center).

**TABLE 11.** Rack configuration of the SICS ICE data center.

| Rack configuration | | | | |
|---|---|---|---|---|
| Number of servers | ΔT, C°(server) | $P_{idle}$, server, W | $P_{max}$, server, W | Number of fans in a server |
| 18 | 12 | 138.8 | 277.7 | 6 |

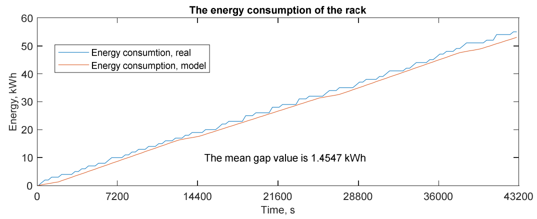


**FIGURE 10.** Comparison of the thermal outputs generated by the model and the real data center.

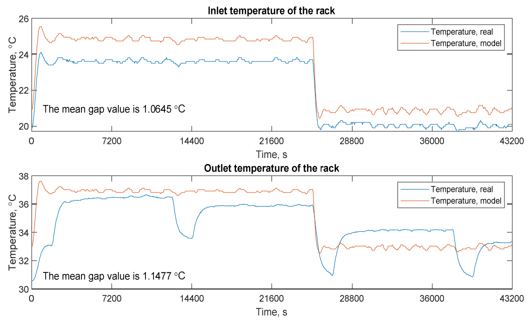


**FIGURE 11.** Comparison of energy consumption of the rack in the model and in the real data center.

## VI. MODEL VALIDATION

This section deals with the validation of the proposed model of a server room. The main point here is the ability of the model to satisfactorily represent thermal behaviour within the server room as well energy consumption of the computational system. To demonstrate adequacy proposed approach, the model of one module of SICS ICE data center [26] is built and results generated by the model are compared with real data collected from the server room of SICS ICE.

Thermal behavior inside the server room is determined as dynamics of two parameters: inlet temperature of racks and outlet temperature of racks. Energy consumption of the computational system is calculated as the sum of energy consumption of all racks. Therefore, it is necessary to build the model of rack utilized in the server room of SICS ICE. The modelled server room comprises of 10 identical racks and 4 CRAH units. Configuration of the rack is presented in Table 11.

The server room has been modelled with equations from Table 2. The inputs for this model are IT-load of all servers and temperature of cold air supplied by CRAH units into the server room. The data for inputs are collected from the SICS ICE server room. For period of 12 hours, the server room has been simulated and results generated by the model have been compared with the respective data from the real server room.

Figure 10 demonstrates the comparison of temperatures of both inlet and outlet generated by the model and collected from SICS ICE. Figure 11 shows the comparison of energy consumption of one rack generated by the model and collected from the real server room. Graphs demonstrate that the model results reflect reality quite well. The mean gap value for rack inlet temperature is 1.1 °C (4.8 %); for rack outlet temperature is 1.15 °C (3.4 %); for energy consumption of rack is 1.5 kWh (5.2 %).

## VII. CONCLUSION

Data center models are used extensively and are being developed in both industry and academia. Often models are specific to the task; sometimes they are not open for others to use or difficult to reproduce with the provided description. Time and effort are spent to develop models for next new research project.

The paper proposed a comprehensive yet open model of data center, building on existing work. It captures configuration and dynamics of servers, server rooms, cooling systems (CRAH, chiller and cooling tower) and connection to the grid. The challenge was to put the pieces of data center together and describe dynamics of each element so that interdependencies between components and parameters are captured correctly and in sufficient details. The model can be used as is or configured with specific equipment. It can be used in various studies from impact of user behavior; to the data center as a smart load in the power grid.

The developed model has been validated on the real data from a medium sized datacenter research facility showing good accuracy. In future work, the validation will be continued on more operation scenarios and different server room configurations, such as: IT load patterns, task categorization, power consumption and cooling dynamics of the servers and data from cooling system. The model will be configured for the corresponding weather conditions at the time of the data acquisition at the data center.

The next steps include following work towards next version of the model: changing averaging algorithm for $T_{outlet\_IT}$, $T_{outlet\_rack}$, and $T_{CRAH\_hot}$ to the algorithm based on enthalpy i.e. flow rate weighted average; extending the model as a function of time; modeling the job generator with patterns of different online users (shopping, games, office work etc.). The future work is to extend model with water storage tank, that will enable flexibility in cooling system. The model should be further extended adding impact of the losses in electrical infrastructure; this will provide full picture of the operating state of the facility. The model can be improved by the community adding more details in the thermodynamics area, server model (RAM, disk space, bandwidth), server room (perforated floors, cold or hot aisle containment) and more. The model is open and has capacity and potential to support new agendas in data center research.

## NOMENCLATURE

| | |
|---|---|
| ICT | Information and Communication Technologies |
| CRAH | Computer Room Air Handling |
| COP | Coefficient of Performance |
| PUE | Power Usage Effectiveness |
| RLU | Rack Location Unit |
| ASHRAE | The American Society of Heating, Refrigerating and Air-Conditioning Engineers |
| RAM | Random Access Memory |
| DVFS | Dynamic Voltage and Frequency Scaling |
| CT | Cooling tower |
| DMI | Datacenter Microgrid Integration |
| SoC | State of Charge |
| PLC | Programmable Logic Controller |
| $P_{server}$ | Power consumption of a server, W |
| $P_{idle}$ | Power consumption of a server in idle mode, W |
| $P_{max}$ | Peak power consumption of a server, W |
| $U$ | Utilization (load) of CPUs of a server, % |
| $P_{rack}$ | Power consumption of a rack, W |
| $N_{s\_r}$ | Number of servers in a rack |
| $f_{air\_server}$ | Required airflow for a server, $m^3$/s |
| $f_{air\_fan\_s}$ | Airflow supplied by one fan of a server, $m^3$/s |
| $N_f$ | Number of fans of a server |
| $P_{fan\_server\_s}$ | Power consumption of one fan of a server, W |
| $\Delta P(Pa)$ | Pressure drop of fan, Pa |
| $\eta$ | Efficiency of fan, % |
| $P_{fan\_server}$ | Power consumption of all fans of a server, W |
| $P_{fan\_rack}$ | Power consumption of all fans of a rack, W |
| $f_{air\_rack}$ | Required airflow for a rack, $m^3$/s |
| $K$ | The re-circulation index, a fraction of air that comes from the server exhaust and re-circulates and mixes with the cool room air supplied by CRAH units |
| $T_{inlet\_k}$ | Temperature at a server inlet, C° |
| $T_{CRAH\_cold}$ | Temperature of cold air supplied by CRAH, C° |
| $\rho_{air}$ | Density of air, kg/$m^3$ |
| $c_{air}$ | Specific heat of air, J/(kg °C) |
| $T_{outlet\_server}$ | Temperature at a server outlet, C° |
| $T_{outlet\_rack}$ | Temperature at a rack outlet, C° |
| $T_{outlet\_IT}$ | Temperature at outlet of racks that a CRAH unit is supposed to cool, C° |
| $P_{IT}$ | Power consumption of all racks in a server room, W |
| $P_{IT\_CRAH}$ | Cooling load of CRAH unit, W |
| $N_{rack\_per\_CRAH}$ | Number of racks corresponding to one CRAH unit |
| $P_{fan\_IT}$ | Power consumption of all fans in a server room, W |
| $N$ | Number of racks in a server room |
| $f_{air\_IT\_CRAH}$ | Airflow supplied by one CRAH unit, $m^3$/s |
| $P_{transit}$ | CPU transition power dissipation, W |
| $P_{short\_circuit}$ | CPU short-circuit power dissipation, W |
| $P_{static}$ | CPU static power dissipation, W |
| $M$ | Constant that captures number of transistors, design parameter and leakage current |
| $V$ | CPU core voltage, V |
| A | Number of transitions per clock cycle (activity factor) |
| $E_{short\_circle}$ | Power of a single short-circuit, W |
| $F$ | Operating frequency of CPU, Hz |
| $C$ | Capacitance of the circuit, F |
| $H$ | Excess heat transfer coefficient |
| *Range* | CRAH unit: the difference between the cold water coming from the chiller ($T_{CW\_cold}$) and hot water returned by the CRAH unit ($T_{CRAH\_hot}$). Taken from the data sheet, measured in C° . Cooling tower: the difference between the water entering ($T_{CT\_hot}$) and leaving cooling tower ($T_{CT\_cold}$). Taken from ASHRAE guidlines, measured in F° . |
| $Q_{CRAH\_calc\_i}$, $Q_{CRAH}$ | Heat load of CRAH unit, heat load of all CRAH units respectively. W |
| $Q_{remain}$ | Heat, that remains in the incoming air/water after the cooling process, W |
| $T_{CRAH\_hot}$ | Temperature of the return warm water of CRAH (to chiller), C° |
| $T_{CW\_cold}$ | Temperature of the incoming refrigerant (water) chilled by the chiller. |
| $\rho_w$ | Density of water (or liquid), kg/$m^3$ |
| $c_w$ | Specific heat capacity of water, J/(kg °C) |
| $f_{water}$ | Water (or liquid) flow, $m^3$/s |
| $f_{water\_CRAH\_i}$ | Water (liquid) flow from single CRAH unit, $m^3$/s |
| $f_{water\_CRAH\_total}$ | Total water (liquid) flow from all CRAH units, $m^3$/s |
| $P_{CRAH\_i}$, $P_{CRAH}$ | Power consumption of CRAH unit, power consumption of all CRAH units, W |
| $Q_{evap}$ | Heat load of a chiller, W |
| $T_{CT\_hot\_limit}$, $T_{CW\_cold\_limit}$ | Operating limits of the chiller: outgoing water temperature towards CRAH ($T_{CW\_cold\_limit}$) and source water outlet temperature ($T_{CT\_hot\_limit}$, cooling tower).C° |
| $T_{CT\_cold}$ | Temperature of cold water coming from cooling tower, C° |
| $T_{CT\_hot}$ | Temperature of hot water returning to cooling tower, C° |
| $Q_{nom}$ | Nominal heat load of given equipment, W |
| $Q_{temp}$ | Auxiliary variable (heat load, W) |
| $P_{chiller}$ | Power consumption of chiller, W |

$Q_{CT}$ Cooling load of cooling tower, W
$T_{approach}$ Approach temperature characterizing a cooling tower, C°
$T_{out}$ Outside temperature, C°
$\lambda_{CT}$ Load of a cooling tower, %
$P_{CT}$ Power consumption of a cooling tower, W
$P_{pumps}$ Power consumption of pumps, W

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