American Journal of Science and Engineering, 2019, Vol-1, Issue-1, 11-20, 2019 in AJSE Publishers (http://ajse.us)

Modeling and Simulation of Data Centers to Predict Behavior

Moises Levy
Department of Computer & Electrical Engineering & Computer Science
Florida Atlantic University. Boca Raton, FL 33431, USA
mlevy2015@fau.edu

***Abstract* – Data center modeling and simulation help to estimate and predict key parameters under certain a-priori known conditions. Data center systems must adopt end-to-end resource management, covering both cyber and physical components. This paper describes a systematic, easy-to-follow approach for data center modeling and simulation using a cyber-physical systems lens. The methodology is aimed to facilitate the estimation of quality of service, airflow and power requirements, and key indicators to assess data centers, and to then compare them to one another, or compare different scenarios under which data centers operate. The results contribute to communicate and better understand data center behavior and areas of improvement.**

Keywords – Data centers, cyber-physical systems, modeling, simulation, airflow, energy, quality of service, workload.

I. INTRODUCTION

Data centers are comprised of information technology equipment (ITE) and supporting infrastructure (e.g., power, environmental control, telecommunications, fire protection, security, and automation). With today's increasing reliance on digital information, data centers' main task is to process and store information securely, and to provide users uninterrupted access to it.

Data centers must satisfy legislation, standards, best practices, and stringent technical requirements in order to guarantee reliability, availability, performance, security, and manage risks. They are frequently provisioned with additional resources to ensure operation under different scenarios. In a data center, numerous threats can cause failures, including human error and technical issues. The impact of failure on a data center is often significant, as lack of access to information entails high costs [1]. Intangible losses, such as business confidence, lost opportunities, and reputation are difficult to quantify.

Data centers are evolving from traditional projects to 'software-defined data centers' (SDDC), where ITE services are delivered as a service, enabled mainly by virtualization and the commoditization of ITE [2]. Another new trend includes 'software-defined power (SDP)' strategies to deliver a power-aware, optimized data center [3]. Modeling and simulation results provide a quantitative explanation of tradeoffs among the different data center components.

The motivation of this paper is to describe a comprehensive data center model, validate the model, and show simulations using a cyber-physical systems perspective, meaning the integration of computational and physical components, potentially including human interaction [4]. This approach is an iterative process, since equipment may be upgraded, added, or removed. Legacy and current generation systems may be in use simultaneously throughout the data center life cycle. A cyber physical system approach for data center modeling and simulation was introduced in papers originally presented at the *IEEE CCWC 2019, the 9th IEEE Annual Computing and Communication Workshop and Conferenc*e [5] [6], for which this work is an extension. The theoretical model serves as the foundation for simulations, to predict the behavior of a hypothetical system, or one where physical measurement and experimentation is not feasible. Results help to assess strategies for end-to-end resource management and key performance indicators improvement.

II. BACKGROUND

Since the deregulation of telecommunications in the U.S. (*Telecommunications Act of 1996* [7]), a number of standards and best practices related to telecommunications, and more recently to the data center industry have emerged to make general recommendations when designing, building or operating a data center. Numerous organizations worldwide have contributed to the creation of standards, white papers, best practices and other documents related to the data centers.

Some of the main publications include the *ANSI/TIA 942-A "Telecommunications Infrastructure Standard for Data Centers"* [8], the *ANSI/BICSI-002 "Data Center Design and Implementation Best Practices"* [9], the "*Data Center Site Infrastructure Standard*" [10] [11], the standard *ANSI/ASHRAE 90.4* "*Energy Standard for Data Centers*" [12], *the* "*Data Center Site Infrastructure Tier Standard: Operational Sustainability*" [13], the "*Data Centre Operations Standard*" (DCOS) [14], the *BICSI-009* "*Data Center Operations and Maintenance Best Practices"*[15], the *Singapore Standard SS 564* (Green Data Centers) [16], *and the ISO/IEC 22237 "Information technology - Data Centre facilities and infrastructures"* [17] [18] [19] [20] [21] [22] [23].

Previous work on data center modeling includes work on specific areas. Work focused on cooling system components include thermal properties [24], heat transfer [25], air temperature [26], air cooling with chillers [27], air conditioning systems [28], and transient thermal behavior [29]. The work in [30] shows a cyber-physical systems approach used for energy efficiency. The work in [31] and [32] present different formulation for energy consumption, and in [33] a feedback control scheduling is explained. The work in [34] and [35] analyze workloads using dynamic resource prediction and allocation, and in [36] workload scheduling with distributed energy is examined. While the related work is of great relevance, it is very specific and does not study the data center's overall behavior. In addition, it does not reflect in the same model a comprehensive understanding of the data centers from workload through the prediction of different parameters (e.g., quality of service, power, airflow, and key indicators).

III. Data Center Modeling

To model a data center it is common practice to fragment it into numerous subsystems, given its complexity. The performance analysis should start with the analysis of each subsystem, and later evaluate the overall behavior of the complete system.

ITE requires power. It consumes energy and generates heat, both of which vary depending on the workload required to be processed. The cooling system cools the facility and extracts the heat. IT resource management systems actively manage the workloads. ITE, power, and cooling systems interact and are controlled by dynamic management of ITE resources.

The approach is comprised of three easy-to-follow steps: (1) modeling the cyber components, (2) modeling the physical components, and (3) identifying data center key indicators.

1. *Modeling the cyber components*

The first step consists of identifying and modeling the components responsible for processing the workloads. These components are defined as 'cyber' components or ITE. The *workload* is the rate and type of jobs processed by the data center as a whole, or by a given piece of ITE. The performance or *processing rate* of ITE is often given in terms of floating-point operations per second (FLOPS), and represents the maximum throughput or the maximum number of jobs that can be processed by the ITE in a unit of time [37].

Workload processed affects energy consumption, which directly impacts the physical environment. A data center that is not processing workload will still consume a fixed amount of energy to maintain the availability of all the resources. As workload increases, energy consumption increases, reaching a maximum where processing time may also rise. Parameters such as workload and ITE specifications can be used to estimate quality of service, power, airflow, energy, and key performance indicators.

1.1. Quality of service.

Quality of service includes variables such as queue length, waiting time, and processing time. The power required by the ITE depends on the workload and the quality of service. A data center with poor quality of service indicators may be unsuitable for the desired purpose.

The *workload arrival rate* (W_{in}) can be interpreted as the number of jobs or instructions arriving to the data center during a given period. Let *nodes (N)* be the total number of computational nodes. Only the active nodes (n) are available at a given time for processing a workload. The *idle nodes* (n_{idle}) represent the ITE which are not processing workload. ITE occupy physical space, require power and airflow, consume energy, generate heat, and require software and maintenance to operate, even when in idle mode.

The total workload arriving at the data center varies with time j and is represented by $W_{in,DC}(j)$. The total workload is distributed among the active nodes through a distribution factor represented by $S(i,j)$. An idle node is represented as a node with no workload to be processed, in other words $S(i,j) = 0$.

The *workload arrival rate* at any active node is the product of $W_{in,DC}(j)$ and $S(i,j)$. The workload departure rate depends on the *processing rate* $PR(i)$ and the workload waiting to be processed or *queue length* $L(i,j)$.

The workload evolution at an active node i at time j is shown in Figure 1 and can be described as follows in terms of *workload arrival rate* $W_{in}(i,j)$, *workload departure rate* $W_{out}(i,j)$, *and queue* $L(i,j)$.

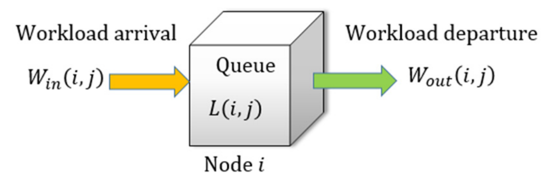

Fig. 1 Workload flow at an ITE node

The *workload arrival rate* at node i at time j considers the total workload arriving at the data center distributed among nodes:

$$W_{in}(i,j) = W_{in,DC}(j) * S(i,j) \tag{1}$$

If the ITE capacity is large enough to process the incoming workload all transactions are processed in real-time, then:

$$\left(W_{in}(i,j) + L(i,j-1)\right) < PR(i) \tag{2}$$

$$W_{out}(i,j) = W_{in}(i,j) + L(i,j-1) \tag{3}$$

$$L(i,j) = 0 \tag{4}$$

Otherwise, if the system is receiving more workload that it can process in real-time, the system is overloaded, and a queue is formed, generating congestion for the jobs to be processed, then:

$$\left(W_{in}(i,j) + L(i,j-1)\right) > PR(i) \tag{5}$$

$$W_{out}(i,j) = PR(i) \tag{6}$$

$$L(i,j) = W_{in}(i,j) + L(i,j-1) - PR(i) \tag{7}$$

The formulation represents the relationships among the *workload departure rate*, the state variable (*queue length*), and the controllable variables (*processing rate* and *workload allocation*) at node i at time j.

In summary, input workload arrives to the data center entering the queue, waits for service from a computational node, and eventually receives the service and then leaves, as shown in Figure 2. Quality of service variables are estimated permanently. The model considers open queuing and first-come-first–serve (FCFS) scheduling to simulate data center behavior, allowing external arrivals and departures of workloads.

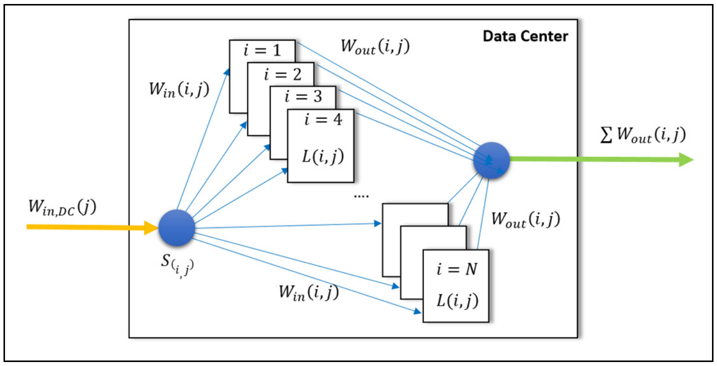

Fig. 2 Workload flow at the data center

Data center analysis is concerned with the way ITE capacity is managed over time. ITE *resource utilization* $U(i,j)$ represents the portion of ITE capacity used to process workload requests. It is estimated as the ratio of the workload processed to the processing rate, expressed in percentage, taking values between 0% and 100%:

$$U(i,j) = W_{out}(i,j)/PR(i) \tag{8}$$

The *average utilization* at time j considers utilization across all nodes.

$$U_{avg,N}(j) = (\sum_{i=1}^{N} U(i,j))/N \tag{9}$$

The idle nodes affect *average utilization* since they are not processing workloads. The *average utilization* considers only active nodes at time j:

$$U_{avg,n}(j) = (\sum_{i=1}^{n} U(i,j))/n \tag{10}$$

Likewise, the *maximum utilization* at time j considers utilization across all nodes:

$$U_{max}(j) = max(U(i,j)) \tag{11}$$

The *waiting time* or queuing time is a measurement of the workload remaining to be processed, and is estimated as the ratio of the length of the workload queue to the processing rate.

$$tw(i,j) = L(i,j)/PR(i) \tag{12}$$

The *average* and *maximum waiting time* are often related to the quality of service offered to the user. The *average waiting time* at time j across all active nodes is defined as:

$$tw_{avg}(j) = (\sum_{i=1}^{n} tw(i,j))/n \tag{13}$$

The *maximum waiting time* at time j across all active nodes is defined as:

$$tw_{max}(j) = max(tw(i,j)) \tag{14}$$

Response time may also be estimated, which is the total time that a workload spends in the system from arrival to service completion. Criteria may be established for workload migration, considering types of workloads, ITE requirements, migration policies, scheduling disciplines, and others. Further, migration of workloads to different data center sites may be considered.

Table 1 summarizes parameters for the cyber components of the model used to estimate quality of service parameters.

TABLE 1. PARAMETERS FOR CYBER COMPONENTS: QUALITY OF SERVICE

Parameter	Description
N	Number of ITE nodes available.
n	Number of active nodes available.
n_{idle}	Number of idle nodes.
$W_{in,DC}(j)$	Workload arrival rate at the data center at time$j$.
$S(i,j)$	Relative amount of workload allocated to the active node i at time j.
$W_{in}(i,j)$	Workload arrival rate at the active node i at time j.
$W_{out}(i,j)$	Workload departure rate at the active node i at time j.
$PR(i)$	Processing rate of node i.
$L(i,j)$	Queue length at node i at time j.
$U(i,j)$	Utilization of node i at time j.
$U_{avg,N}(j)$	Average utilization across all nodes at time j.
$U_{avg,n}(j)$	Average utilization across all active nodes at time j.
$U_{max}(j)$	Maximum utilization of node i at time j.
$t_w(i,j)$	Waiting time at node i at time j.
$tw_{avg}(j)$	Average waiting time at time j.
$tw_{max}(j)$	Maximum waiting time at time j.

1.2. Power

In general, processors and memory are the main power consumers for a data center server, followed by power supply loss, storage, PCI (peripheral component interconnect), motherboard, fans, and networking interconnects [38]. Processor power consumption varies by processor, workload, and power management technologies [38].

Most server workloads scale linearly from idle to maximum power. *CPU power consumption* can be estimated based on processor utilization. This approximation has shown to be true within a 5% margin of error [38].

$$P_{CPU}(i,j) = \left(P_{CPU\_max}(i) - P_{CPU\_idle}(i)\right) * U_{CPU}(i,j) + P_{CPU\_idle}(i) \tag{15}$$

Memory-related power consumption depends on the specific technology, the idle and active states, as wells as the workloads[38]. Processor and memory cooling is challenging, requiring thermal analysis, which includes power, airflow, temperature, and humidity.

Storage power consumption can be significant, depending on the quantity and technology of drives present. Average hard disk power consumption can be estimated as the weighted sum of the power required in idle, write, read, and seek states [38]. The variables w_1, w_2, w_3, and w_4 represent the respective weights, with values ranging between 0 and 1. The weights depend on the specific use, such as average office work or intensive storage operations (e.g., defragmentation, scanning the surface, copying).

$$P_S(i,j) = w_{1(i,j)} * P_{S_{idle}}(i) + w_{2(i,j)} * P_{S_{wr}}(i) + w_{3(i,j)} * P_{S_{read}}(i) + w_{4(i,j)} * P_{S_{seek}}(i) \tag{16}$$

Power supply efficiency depends on the current load. The optimal load is around 50% to 75%, efficiency drops dramatically for loads below 50%, and it does not really improve for loads higher than 75%. Power supply efficiency is typically profiled with high load factors (e.g., 80% to 90%), which may not be realistic. In a data center, *power supply efficiency loss* is considerable, since server workloads fluctuate, and servers do not perform at full capacity most of the time [38].

Power consumption characterization for various workloads can be valuable. Studies with different servers and workloads have concluded that ITE power consumption closely follows processor utilization [38]. The *ITE power* requirement over time can be assumed linear from idle (P_{idle}) to maximum (P_{max}) power as workload increases. *ITE power* depends on the workload, and therefore is estimated based on its utilization *(U)*:

$$P_{ITE}(i,j) = \left(P_{max}(i) - P_{idle}(i)\right) * U(i,j) + P_{idle}(i) \tag{17}$$

The *power required* $P_{ITE}(j)$ by all nodes at time j is:

$$P_{ITE}(j) = \sum_{i=1}^{N} P_{ITE}(\mathrm{i},\mathrm{j}) \tag{18}$$

The formulation supports the development of energy management strategies for various ITE. The *energy consumption* $E(i,j)$ at node i at time j is described in a discrete or continuous system as:

$$E(i,j) = \sum_{t=0}^{j} P_{ITE}(i,t) * \Delta t \text{ and} \tag{19}$$

$$E(i,j) = \int_0^j P_{ITE}(i,t) * dt \text{, respectively.} \tag{20}$$

The *energy consumption* $E(j)$ by all nodes at time j is:

$$E(j) = \sum_{i=1}^{N} \mathrm{E}(\mathrm{i},\mathrm{j}) \tag{21}$$

Previously, maximum power consumption was around two times idle consumption. Newer technologies for processor designs improve this measurement to a factor of five, and are fast approaching ten, with further expected improvements [39]. This is a great achievement in terms of ITE energy efficiency, since less energy is consumed in the idle state.

Table 2 summarizes parameters for the power model required for the cyber components of a data center.

TABLE 2. PARAMETERS FOR CYBER COMPONENTS: POWER

Parameter	Description
$P_{CPU}(i,j)$	Power required by the CPU at node i at time j.
$P_{CPU\_idle}(i)$	Power required by the CPU at node i for the idle state.
$P_{CPU\_max}(i)$	Maximum power required by the CPU at node i.
$U_{CPU}(i,j)$	Utilization of the CPU at node i at time j.
$P_S(i,j)$	Power required by storage at node i at time j.
$P_{S_{idle}}(i)$	Power required by storage at node i for the idle state.
$P_{S_{wr}}(i)$	Power required by storage for writing tasks at node i.
$P_{S_{read}}(i)$	Power required by storage for reading tasks at node i.
$P_{S_{seek}}(i)$	Power required by storage for seeking tasks at node i.
$w_1(i,j)$	Weight at node i at time j for the idle state.
$w_2(i,j)$	Weight at node i at time j for writing tasks.
$w_3(i,j)$	Weight at node i at time j for reading tasks.
$w_4(i,j)$	Weight at node i at time j for seeking tasks.
$P_{ITE}(i,j)$	Power required by node i at time j.
$P_{idle}(i)$	Power required by node i for the idle state.
$P_{max}(i)$	Maximum power required by node i.
$U(i,j)$	Utilization of node i at time j.
$E_{ITE}(i,j)$	Energy consumption at node i until time j.

Variation in ITE power requirements related to the temperature of the air intake may be considered. Based on experimental results in [40], it is shown that power requirement of the server increases if the temperature of the air intake is increased. As an example, if the server inlet temperature is increased from 15 ºC to 35 ºC, an increase of the power required by the server is expected in a range of 7% to 20%.

2. Modeling the physical components

The second step consists of modeling the physical, mainly known as thermal components, including airflow and power requirements. 'Cyber' and thermal components are coupled through the energy consumption of ITE. Thermal behavior is affected by the power required by ITE, which depends on the workload processed and quality of service.

2.1. Airflow

ITE must satisfy operating conditions to guarantee their desired performance, reliability, and life expectancy. Airflow predictions involve thermodynamics concepts [41]. Most of the power drawn by ITE is dissipated as heat. In data centers, cold air from the cooling system absorbs heat generated mainly by ITE, and the warm air returns to the cooling system. The heat is then dissipated outside the facility. Figure 3 shows an airflow example, considering a data center with a raised floor and a cold/hot aisle configuration (cold air inlets of the cabinets face the same side, and hot air exhaust faces the same side).

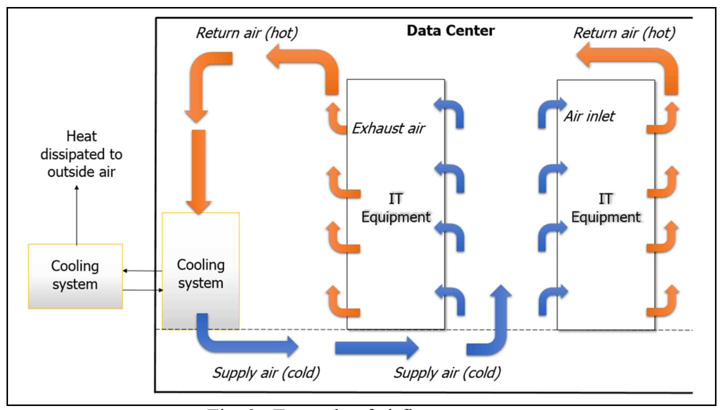

Fig. 3 Example of airflow management

The cooling system inside the data center (CRAC -*computer room air conditioner*- or CRAH -*computer room air handler*-) supplies cold air to the air inlets of the ITE cabinets through the raised floor. Exhaust (hot) air is returned to the cooling system unit for further heat exchange through the outside unit (e.g., condenser or chiller plant).

The airflow rate supplied by the cooling system usually exceeds the total airflow required by ITE. However, understanding airflow requirements for the ITE may optimize the airflow management from the cooling system. The airflow travels through the air inlet of the ITE to cool it down via convection and is exhausted as hot air. The convective heat transfer at the ITE can be described as [41]:

$$q = Cp * W * \Delta T \tag{22}$$

The *amount of heat transferred (q)* is estimated as the power drawn by the ITE. The *mass flow (W)* is the *airflow rate (Af)* multiplied by the *density of air* (ρ). The *specific heat* (Cp) and *density of air* (ρ) are dependents of the temperature. The *temperature rise* (ΔT) is the difference between the intake air and exhaust air temperatures. The previous equation can then be expressed at node i at time j as:

$$P_{ITE}(i,j) = Cp * Af(i,j) * \rho * \Delta T(i,j) \tag{23}$$

Therefore, manipulating the previous equation, the estimated *airflow* required is:

$$Af(i,j) = P_{ITE}(i,j) / \left(Cp * \rho * \Delta T(i,j)\right) \tag{24}$$

Considering a temperature of 25 ºC (or 77 ºF) and standard atmospheric pressure (1 atm.), the specific heat (Cp) is *1005 Joule/ (Kg·ºC)* and the density of air (ρ) is *1.184 Kg/m³*.

The airflow requirement (in cfm -cubic feet per minute-) is estimated as a constant multiplied by the ratio of the power of ITE and the temperature rise:

$$\begin{aligned} Af(i,j)_{\text{cfm}} &= 1.78 * P_{ITE}(i,j) \,/\, \Delta T(i,j)_{\circ\text{C}} \\ &= 3.20 * P_{ITE}(i,j) \,/\, \Delta T(i,j)_{\circ\text{F}} \end{aligned} \tag{25}$$

If the temperature rise is unknown, it may be estimated at 20 ºC, to guarantee the reliable performance of the components [42], which results in approximately 9 cfm per 100 W of heat generated. The best practice to estimate the airflow is using real-time measurements for power and temperature rise.

The *total airflow* required by ITE in a data center must include all the nodes, and can be described as:

$$Af(j) = \textstyle\sum_{i=1}^{N} P_{ITE}(i,j) / \left(Cp * \rho * \Delta T(i,j)\right) \tag{26}$$

$$\begin{aligned} Af(j)_{\text{cfm}} &= \textstyle\sum_{i=1}^{N} 1.78 * P_{ITE}(i,j) / \Delta T(i,j)_{\circ\text{C}} \\ &= \textstyle\sum_{\text{i}=1}^{\text{n}} 3.20 * \text{P}_{\text{ITE}}(\text{i},\text{j}) / \Delta T(i,j)_{\circ\text{F}} \end{aligned} \tag{27}$$

Table 3 summarizes the model parameters for airflow of the cooling system.

TABLE 3. PARAMETERS FOR THERMAL COMPONENTS: AIRFLOW

Parameter	Description
q	Amount of heat transferred (W).
Cp	Specific heat of air (Joule/ (Kg * ºC)).
ρ	Density of air (Kg / m³).
W	Mass flow (Kg / min).
ΔT	Temperature rise of air (°C or °F).
$\Delta T(i,j)$	Temperature rise of air at node i at time j (°C or °F).
$P_{ITE}(i,j)$	Power required (W) by node i at time j.
$Af(i,j)$	Airflow (cfm) through the air inlet of the ITE at node i at time j.
$Af(j)$	Airflow (cfm) required by all ITE at time j.

The formulation helps to identify opportunities to optimize airflow management and the cooling system. As the heat generated by ITE increases, the airflow rate may also increase to maintain temperature requirements. Most new ITE have variable-speed fans with control algorithms dependent on the utilization of the resource [43].

For the purpose of the model, it is assumed that there is no mixing between cold air and hot air, or that the mixing can be neglected, as it will not affect the temperature of the return air to the cooling system. In case the previous assumption does not hold, the temperature of the return air may be estimated considering the airflow management through computational fluid dynamics with the desired simplifications.

2.2. Power

The total cooling capacity of a cooling system can be expressed as the sum of sensible and latent heat removed. The cooling load in data centers is mainly sensible heat, generated by ITE, lights, and motors. Latent heat can be dismissed, as there are few people inside the data center and limited outside air. The sensible heat ratio is the ratio of sensible cooling to total cooling. On a scale from 0 to 1, it usually takes high values, ranging between 0.9 and 1. This is one of the main reasons for using precision cooling systems, designed for highly sensible heat ratios, as opposed to comfort cooling systems. In addition, precision cooling systems operate at higher airflow, satisfy strict temperature and humidity controls, and run continuously [44][45].

The majority of the power consumption in the cooling system stems from compressors (in the chillers or CRAC units), chilled and cooling tower water pumps, cooling tower or heat exchange blowers, and air handling unit blowers [46].

The *sensible coefficient of performance ($SCOP$)* is used to estimate the power requirements of the cooling system. The $SCOP$ is the ratio of net sensible cooling capacity to the power required to produce that cooling (excluding reheat and humidifier) [47] [48]. The $SCOP$ values for commercial precision cooling systems without economizers usually range from 1.8 to 3.8 [49].

The $SCOP$ is also dependent on the technical characteristics of the cooling system and the temperature of the cold air supplied. For example, for a specific water chilled CRAC unit where T_C is the temperature of the supplied air [50], it can be modeled as:

$$SCOP = 0.0068 * {T_C}^2 + 0.0008 * T_C + 0.458 \tag{28}$$

The amount of power required by the cooling system (P_{AC}) is the ratio of total heat loads to $SCOP$. The total heat loads are the sum of all power delivered to the ITE, lighting, and electrical distribution losses. For the sake of explanation, since power needs are time-dependent, we assume time j, although it is not indicated for each one of the terms in the following equations.

$$P_{AC} = \left(\sum P_{ITE} + \sum P_{Lighting} + \sum P_{Losses}\right) / SCOP \tag{29}$$

Lighting power ($P_{Lighting}$) is dependent on the lighting power density, technology, and controls. It can be assumed as 1% of the total *power required by the ITE* (P_{ITE}) [51] [52].

$$\sum P_{Lighting} = 0.01 * \sum P_{ITE} \tag{30}$$

Electrical distribution systems are assumed to have a constant loss of 2% of the *total power required by ITE (P_{ITE})*. If a UPS is present, 2% is added to UPS losses [51]. The *UPS losses* are one minus the *UPS efficiency (η_{UPS})*, and depend on factors such as the UPS technology type, size, voltage, and load factor. UPS efficiency usually ranges from 65% to 97% [52]. *Electrical distribution system losses* (P_{Losses}) are defined as:

$$\sum P_{Losses} = \left(0.02 + (1 - \eta_{UPS})\right) * \sum P_{ITE} \tag{31}$$

Therefore, considering ITE, lighting, and electrical distribution losses, the amount of *power required by the cooling system* can be estimated as:

$$P_{AC} = (2.03 - \eta_{UPS}) * \sum P_{ITE} \ / \ SCOP \quad (32)$$

As a simplification, if the total heat load is considered only as the sum of all power required for the ITE, then:

$$P_{AC} = \sum P_{ITE} \ / \ SCOP \quad \text{or} \quad (33)$$

$$P_{AC}(j) = \sum_{i=1}^{N} P_{ITE}(i,j) \ / \ SCOP \quad (34)$$

In addition, the cooling system must consider the amount of airflow required by ITE based on workloads, utilization, and power requirements. The affinity laws for fans are used to estimate the power required by similar fans in relation to airflow [53]. The first one states that the airflow is proportional to fan speed:

$$Af_{FAN\_1}/Af_{FAN\_2} = N_{FAN\_1}/N_{FAN\_2} \quad (35)$$

And the second states that the power is proportional to the cube of the fan speed:

$$P_{FAN\_1}/P_{FAN\_2} = \left(N_{FAN\_1}/N_{FAN\_2}\right)^3 \quad (36)$$

Then, the fan power requirement is proportional to the cube of the airflow supplied:

$$P_{FAN\_1}/P_{FAN\_2} = \left(Af_{FAN\_1}/Af_{FAN\_2}\right)^3 \quad (37)$$

These estimations lead to energy management strategies when various fans are present in the data center. Consider a data center with just one CRAH unit. If the airflow required by the ITE is reduced by half, the power required by the CRAH unit is reduced by a factor of 8. Further, the data center usually has more than one CRAH unit, and the airflow required by the ITE may be supplied by multiple units, instead of just one unit.

Data center layout, cooling system, and ITE must be considered to understand airflow management requirements. Different strategies such as air economizers or free cooling may be implemented to reduce the power required for the cooling system [43].

Table 4 summarizes the model parameters for the cooling systems.

TABLE 4. PARAMETERS FOR THERMAL COMPONENTS: POWER

Parameter	Description
SCOP	Sensible Coefficient of Performance for the cooling system.
T_C	Temperature of the supplied air (or cold air) by the cooling system (°C).
P_{AC}	Power required by the cooling system (W).
P_{ITE}	Power required by ITE(W).
$P_{Lighting}$	Power required by lighting (W).
P_{Losses}	Electrical distribution system losses (W).
η_{UPS}	Efficiency of the UPS.
Af_{FAN}	Airflow capacity of the fan (cfm).
N_{FAN}	Speed of the fan (rpm).
P_{FAN}	Power required by the fan (W).

3. *Identifying data center key indicators.*

The last step consists of recognizing key indicators for the data center. Several metrics can help to examine efficiency, productivity, sustainability, operations, and risk, indicators for which the user must determine an acceptable level [54] [55]. For the sake of the explanation, the *Power Usage Effectiveness (PUE)* metric is used as an example of key indicator, since it is one of the most widely used energy efficiency metrics. Figure 4 shows the energy flow in a data center.

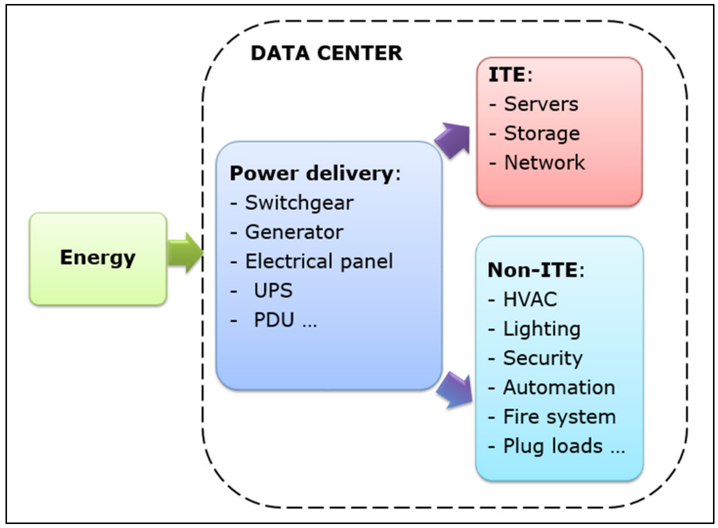

Fig. 4 Data center energy flow diagram

Right-sizing the data center based on modeling, simulation and projections of ITE utilization may not be accurate. Also, specific needs may change rapidly. Real-time monitoring of the data center may help to calibrate and validate models and simulations. This is made possible given that data center monitoring and management systems collect data (e.g., power delivered for ITE, power required by the total facility, airflow, ITE utilization) in real-time [56] [57]. Gathering the relevant data and understanding its nature is more important than simply collecting more data [58].

One of the most widely used energy efficiency metrics is *Power Usage Effectiveness (PUE)* [59], defined as the ratio of energy used in a facility to energy delivered to ITE. The ideal PUE is one. In terms of the average power required by the data center (P_{DC}) and the ITE (P_{ITE}), using the same measurement period, it can be expressed as:

$$PUE = P_{DC} \ / \ \sum P_{ITE} \quad (38)$$

The power required to operate a data center can be simplified as the summation of the power required by the ITE and the cooling system. Electrical distribution system losses and other systems (e.g., lighting) are neglected.

The $DCiE$ metric can be expressed in terms of power required by the ITE (P_{ITE}) and the cooling system (P_{AC}) as:

$$PUE = \left(\sum P_{ITE} + \sum P_{AC}\right) \ / \ \sum P_{ITE} \quad (39)$$

Considering a cooling system comprising CRAC units, the $DCiE$ metric can be expressed as a function of the *sensible coefficient of performance (SCOP)* of the cooling system (CRAC), the power required by the ITE P_{ITE} and the cooling system P_{CRAC}:

$$PUE = \left(\sum P_{ITE} + \sum P_{CRAC}\right) \ / \ \sum P_{ITE} \quad (40)$$
$$= 1 + 1 \ / \ SCOP$$

Another scenario may consider a cooling system comprising a chiller water plant and CRAH units, the PUE metric can be expressed as as a function of the *sensible coefficient of performance* $(SCOP)$ of the cooling system (chiller), the power required by the ITE P_{ITE}, the chiller water plan $P_{Chiller}$ and the CRAH units (fans) P_{Fan}:

$$DCiE = \sum P_{ITE} / (\sum P_{ITE} + \sum P_{Chiller} + \sum P_{Fan}) \quad (41)$$

$$= \sum P_{ITE} / (\sum P_{ITE} + \sum P_{ITE} / SCOP + \sum P_{Fan})$$

The behavior of the $SCOP$ is nonlinear and usually decreases with lower temperatures. To supply colder air, the cooling system consumes more energy. Therefore, as we increase the temperature of the cold air supplied by the cooling system, the $SCOP$ increases, and the PUE decreases. There are limits imposed by climate analysis, cooling system type, ITE requirements (e.g., ASHRAE temperature range and maximum rate of change recommendations [40] [60] [61]), and airflow management.

IV. Model Validation

It is important to validate and understand the accuracy of the formulation for power and airflow requirements, which are relevant for data center design. Information from a computer manufacturer was used to validate the model formulation. It is worth noting that this information may not be available for all ITE from all manufacturers, in which case proper experiments should be developed if needed.

Two different rack servers are selected for comparison, the DELL PowerEdge R740 [62] with maximum power of 271 W and idle power of 104 W, and the DELL PowerEdge R940xa [63] with maximum power of 563 W and idle power of 165 W, both with the temperature set to 25 ºC. Data from the manufacturer for these rack servers was gathered through an infrastructure planning tool [64] [65].

Information provided by the manufacturer for the ITE includes maximum power (P_{max}), idle power (P_{idle}), ambient temperature, and for different values of utilization (U) the input power and airflow requirements, and the temperature rise (ΔT). The input power (P_{ITE}) and airflow (A_f) requirements are also estimated at different values of utilization (U) using model formulation (equations 17 and 27).

Figures 5 and 6 show the different parameters from the manufacturer and the formulation model. Data from the manufacturer is compared against the results from the formulation model, and their respective absolute margin of error is calculated. For the ITE mentioned, the model is accurate within a 20% margin of error, and with greater precision (less than 7% margin of error) if the utilization is greater than 50%.

Rack Server from DELL: PowerEdge R740
P max (W): 271   P idle (W): 104
Temp (oC): 25

	Data from maufacturer			Formulation from model			
% Utilization	Input Power (W)	Airflow (CFM)	Temp. rise (oC)	Input Power (W)	Error	Airflow (CFM)	Error
0%	104.00	33.10	5.7	104.00	0.0%	32.48	1.9%
10%	143.00	39.90	6.5	120.70	15.6%	33.05	17.2%
20%	166.00	43.00	7.0	137.40	17.2%	34.94	18.7%
30%	177.00	44.30	7.2	154.10	12.9%	38.10	14.0%
40%	190.00	45.80	7.5	170.80	10.1%	40.54	11.5%
50%	199.00	46.80	7.6	187.50	5.8%	43.91	6.2%
60%	207.00	47.80	7.8	204.20	1.4%	46.60	2.5%
70%	222.00	49.50	8.1	220.90	0.5%	48.54	1.9%
80%	237.00	51.10	8.3	237.60	0.3%	50.96	0.3%
90%	254.00	53.40	8.6	254.30	0.1%	52.63	1.4%
100%	271.00	55.30	8.8	271.00	0.0%	54.82	0.9%

Fig. 5 Parameters for DELL PowerEdge R740

Rack Server from DELL: PowerEdge R940xa
P max (W): 563   P idle (W): 165
Temp (oC): 25

	Data from maufacturer			Formulation from model			
% Utilization	Input Power (W)	Airflow (CFM)	Temp. rise (oC)	Input Power (W)	Error	Airflow (CFM)	Error
0%	165.00	106.10	2.8	165.00	0.0%	104.89	1.1%
10%	230.00	109.80	3.8	204.80	11.0%	95.93	12.6%
20%	288.00	122.30	4.2	244.60	15.1%	103.66	15.2%
30%	313.00	127.10	4.4	284.40	9.1%	115.05	9.5%
40%	344.00	132.50	4.7	324.20	5.8%	122.78	7.3%
50%	363.00	136.00	4.8	364.00	0.3%	134.98	0.7%
60%	383.00	139.20	5.0	403.80	5.4%	143.75	3.3%
70%	418.00	144.50	5.2	443.60	6.1%	151.85	5.1%
80%	453.00	149.40	5.5	483.40	6.7%	156.45	4.7%
90%	503.00	155.70	5.8	523.20	4.0%	160.57	3.1%
100%	563.00	162.30	6.2	563.00	0.0%	161.64	0.4%

Fig. 6 Parameters for DELL PowerEdge R940xa

V. Data Center Simulation

Simulation models help predict the behavior of the different components of a data center, and may assist operators to attain the desired data center performance. Simulations help understand tradeoffs between the data center's performance and costs.

After the formulation and implementation of the simulation model (e.g., MATLAB or Simulink tools) [6], the next steps include the design of experiments and analysis of simulation results. Simulations show the diverse quality of service parameters, utilization of ITE, power and airflow requirements, energy consumption, and as well other values as needed. The quality of service shows how the workload is being processed. In general, lower values represent higher performance. ITE specifications such as processing rate, power idle and power maximum, are usually related to the generation and the cost of ITE. The power requirements of ITE and airflow affect the cooling system performance. The energy consumption is mainly related to the operational expenses.

Depending on the needs, different hypothetical data center scenarios may be considered including various workload and ITE. The first challenge is to understand the type and the duration of the workload. Figure 7 shows examples of three different input signal types (normal, constant or random) to simulate the workload behavior.

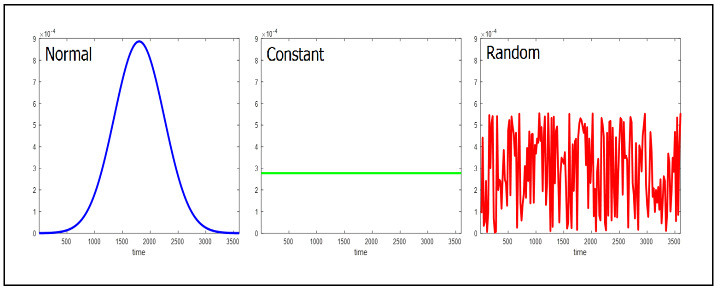

Fig. 7 Workload input signal types

The parameters of the workload input signal following a normal or Gaussian function are defined as:

$$f(t) = \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-(t-\mu)^2}{2\sigma^2}} \tag{42}$$

Where $1/(\sigma\sqrt{2\pi})$ represents the height of the curve's peak, µ is the position of the center of the peak, and σ controls the width of the curve. The parameters µ and σ are user-defined. For the simulations values of $\mu = T_f/2$ and $\sigma = T_f/8$ are assumed, where T_f represents the duration of the workload input.

For the constant signal, the constant function with a value of $1/T_f$ can be used. And for the random signal, a uniform random number function between 0 and $2/T_f$ can be used.

The different coefficients for the workload input signals are established so the integral of these functions between 0 and Tf is approximately one. This is multiplied by a scale factor to achieve the desired total workload input. Consequently, the simulations can consider the same total workload for different workload input signal types.

As an example; consider a simulation with the following parameters: two nodes, workload input signal as a Gaussian function for one hour, sampling rate of one second, input scaler equal to 250, and uneven relative amount of workload among nodes (S = 30% , 70%). Identical power specifications for ITE resources (P_{idle}= 50 W , P_{max}= 200 W), but different processing rates (PR = 50 , 80 jobs/s). Different graphs can be obtained through the simulations to understand the behavior. Figure 8 shows the behavior of workload input versus workload output and queues. At the beginning, the ITE are able to process all the workload input in real-time, so the workload output follows the workload input. After, the system is overloaded, the ITE is receiving more workload than it can process in real-time, generating congestion for the jobs to be processed, and a queue is formed. The queue is different for each ITE, since they are processing 30% and 70% of the workload input respectively, and at different processing rates. Figure 9 shows the workload output and utilization per computational node. Figure 10 shows the waiting time per computational node, and the average and maximum waiting time system-wide. Lastly, Figure 11 shows the overall power and airflow requirements for ITE, and the energy consumption by ITE.

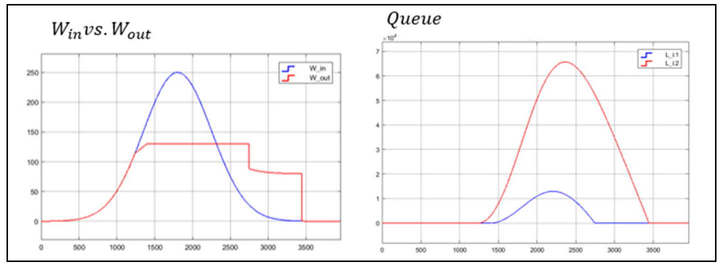

Fig. 8 Workload and queue graphs.

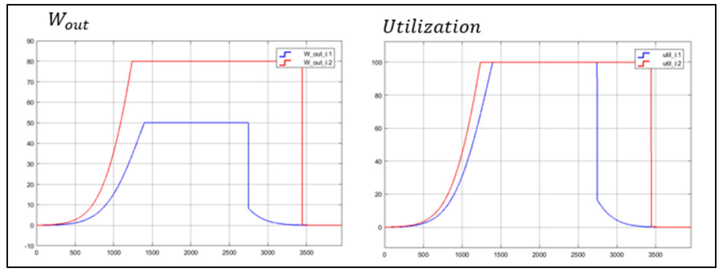

Fig. 9 Workload output and utilization graphs.

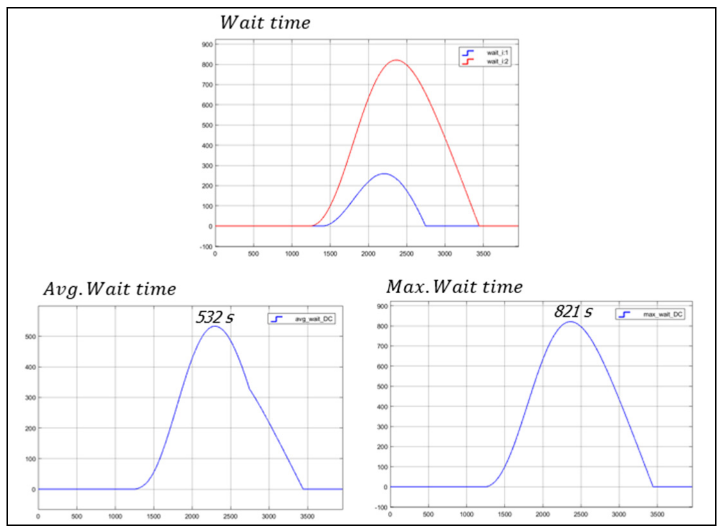

Fig. 10 Waiting time graphs.

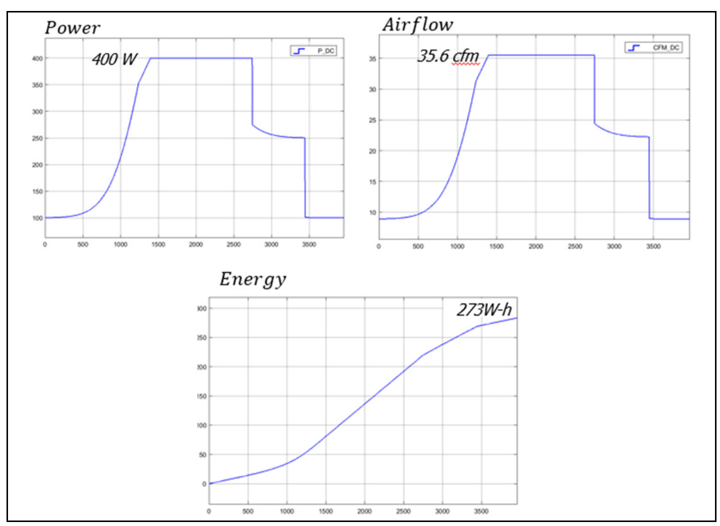

Fig. 11 Power, airflow and energy graphs.

To better understand the behavior of the data center under different conditions, multiple scenarios may be generated using the simulation model. For example, different number of nodes (1 to 50), different total workload input (10^5 to 10^7 jobs/s) can be considered, a workload input with the Gaussian function for one hour, and equal node distribution. Identical specifications for ITE resources: P_{idle}= 50 W, P_{max}= 200 W, and PR= 50 jobs/s. Figure 12 shows the results through 3D graphs. The different scenarios consider the total workload, the number of nodes, and the other axis, which is the total run time, the total energy consumption or the maximum waiting time.

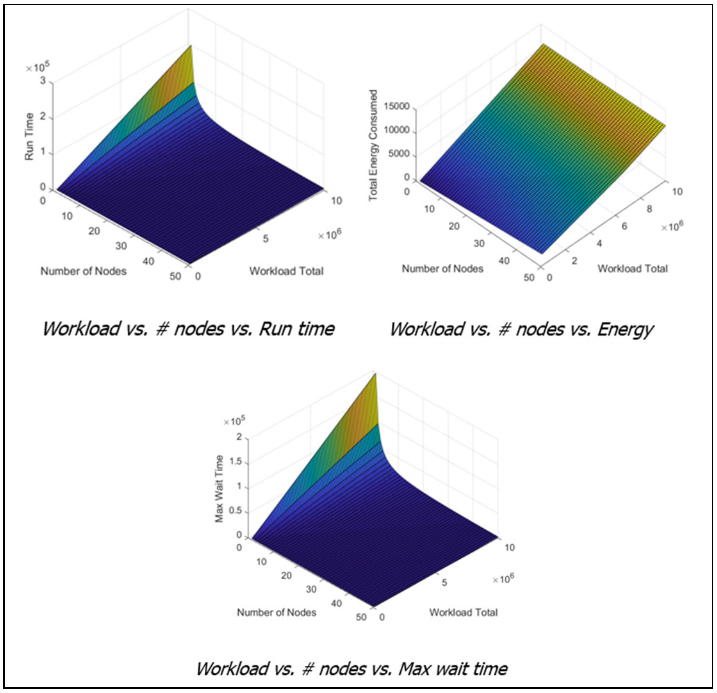

Fig. 12 Power, airflow and energy graphs.

High workloads with high number of ITE, result in good values for quality of service (e.g., low values for run time and maximum waiting time) but at higher costs (e.g., more ITE, as well as greater power and airflow requirements). High workloads and low number of ITE result in worse values for the quality of service parameters (e.g., high values for run time and maximum waiting time), at around the same operational costs (e.g., energy consumption) but with fewer ITE (lower capital expenditures).

The simulations described for the different hypothetical scenarios shows quantitatively that a data center at a certain time may be ideal given some premises, such as workloads, node distribution and ITE; however, when conditions change, performance is affected and the same data center may not be optimal.

VI. Conclusions

Modeling contributes to better understanding data center behavior, tradeoffs and impacts of under different assumptions. The model and simulations described, using a cyber-physical systems lens, involves a comprehensive view of a data center. Depending on each specific data center configuration and operations, the model assumptions may need to be revised. Results help to identify strategies to improve end-to-end resource management and key performance indicators.

Since right-sizing the data center based on modeling and simulations may not be accurate, and specific needs may change rapidly, real-time monitoring of the data center may help to calibrate and validate models.

VII. Future Research

Future work may consider calibrating and validating the theoretical model with real data from different manufacturers and experiments, for numerous ITE. It may also reflect different assumptions for the model.

Data center systems must include end-to-end resource management, covering both the cyber and the physical components. Multi-objective optimization, including quality of service and energy consumption is a desirable goal, since the requirements of data center components change continuously with time. There are currently no simulation solutions available that consider a cyber-physical approach, which also include security and risk assessment. New simulation tools are needed to support these capabilities.

References

[1] Ponemon Institute LLC, “Cost of data center outages. Data center performance benchmark series,” 2016.
[2] Dell Inc., “The software-defined data center: a paradigm shift in data center deployment. White paper,” 2015.
[3] BNP Media Inc, “The time is now for software defined power,” *Mission Critical. Data center and mission-critical solutions*, vol. 11, no. 3. pp. 20–23, 2018.
[4] National Science Foundation, “Cyber-physical systems (CPS).” [Online]. Available: https://www.nsf.gov/publications/pub_summ.jsp?ods_key=nsf18538&org=NSF. [Accessed: 10-May-2019].
[5] M. Levy, D. Raviv, and J. O. Hallstrom, “Data center modeling using a cyber-physical systems lens,” *2019 IEEE 9th Annual Computing and Communication Workshop and Conference (CCWC)*. Las Vegas, NV, 2019.
[6] M. Levy, D. Raviv, and J. Baker, “Data center simulations deployed in MATLAB and simulink using a cyber-physical systems lens,” *2019 IEEE 9th Annual Computing and Communication Workshop and Conference (CCWC)*. Las Vegas, NV, 2019.
[7] The Senate of the United States. 104th Congress (1995-1996), *Telecommunications Act*. 1996.
[8] “Telecommunications infrastructure standard for data centers,” ANSI/TIA-942-B, 2017.
[9] “Data center design and implementation best practices,” ANSI/BICSI 002, 2019.
[10] P. Turner, J. H. Seader, V. Renaud, and K. G. Brill, “Tier classifications define site infrastructure performance,” Uptime Institute, 2006.
[11] “Data center site infrastructure tier standard: topology,” Uptime Institute, 2018.
[12] “Energy standard for data centers,” ANSI/ASHRAE 90.4, 2016.
[13] “Data center site infrastructure tier standard: operational sustainability,” Uptime Institute, 2014.
[14] “DCOS - Data Centre Operations Standard,” EPI, 2016.
[15] “Data center operations and maintenance best practices,” BICSI 009, 2019.
[16] “Green data centres – Part 1: energy and environmental management systems,” Singapore Standards SS 564, 2013.
[17] “Information technology - Data centre facilities and infrastructures. Part 1: general concepts,” ISO/IEC TS 22237-1, 2018.
[18] “Information technology - data centre facilities and infrastructures. Part 2-1: building construction,” ISO/IEC TS 22237-2, 2018.
[19] “Information technology - Data centre facilities and infrastructures. Part 3: power distribution,” ISO/IEC TS 22237-3, 2018.

[20] "Information technology - Data centre facilities and infrastructures. Part 4: environmental control," ISO/IEC TS 22237-4, 2018.

[21] "Information technology - Data centre facilities and infrastructures. Part 5: telecommunications cabling infrastructure," ISO/IEC TS 22237-5, 2018.

[22] "Information technology - Data centre facilities and infrastructures. Part 6: security systems," ISO/IEC TS 22237-6, 2018.

[23] "Information technology - Data centre facilities and infrastructures. Part 7: management and operational information," ISO/IEC TS 22237-7, 2018.

[24] S. U. R. Malik, K. Bilal, S. U. Khan, B. Veeravalli, K. Li, and A. Y. Zomaya, "Modeling and analysis of the thermal properties exhibited by cyberphysical data centers," *IEEE Syst. J.*, vol. 11, no. 1, pp. 163–172, 2017.

[25] V. López and H. F. Hamann, "Heat transfer modeling in data centers," *International Journal of Heat and Mass Transfer*, vol. 54, no. 25–26. pp. 5306–5318, 2011.

[26] R. Ghosh and Y. Joshi, "Dynamic reduced order thermal modeling of data center air temperatures," *Proceedings of the ASME InerPACK*. Portland, OR, pp. 423–432, 2011.

[27] T. J. Breen, E. J. Walsh, and J. Punch, "From chip to cooling tower data center modeling: part I. Influence of server inlet temperature and temperature rise across cabinet," 2010.

[28] R. Anton, H. Jonsson, and B. Palm, "Modeling of air conditioning systems for cooling of data centers," in *ITherm 2002. Eighth Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems*, 2002, pp. 552–558.

[29] G. Varsamopoulos, M. Jonas, J. Ferguson, J. Banerjee, and S. K. S. Gupta, "Using transient thermal models to predict cyberphysical phenomena in data centers," *Sustain. Comput. Informatics Syst.*, vol. 3, no. 3, pp. 132–147, 2013.

[30] L. Parolini, B. Sinopoli, B. H. Krogh, and Z. Wang, "A cyber–physical systems approach to data center modeling and control for energy efficiency," in *Proceedings of the IEEE*, 2012, vol. 100, no. 1, pp. 254–268.

[31] M. Dayarathna, Y. Wen, and R. Fan, "Data center energy consumption modeling: a survey," *IEEE Communications Surveys & Tutorials*, vol. 18, no. 1. pp. 732–794, 2016.

[32] A. Beloglazov, R. Buyya, Y. C. Lee, and A. Zomaya, *A taxonomy and survey of energy-efficient data centers and cloud computing systems*, vol. 82. Elsevier Inc., 2010.

[33] X. Zhao *et al.*, "Feedback control scheduling in energy-efficient and thermal-aware data centers," *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, vol. 46, no. 1. pp. 48–60, 2016.

[34] F. Tseng, X. Wang, L. Chou, H. Chao, S. Member, and V. C. M. Leung, "Dynamic resource prediction and allocation for cloud data center using the multiobjective genetic algorithm," *IEEE Systems Journal*, vol. PP, no. 99. pp. 1–12, 2017.

[35] A. M. Al-Qawasmeh, S. Pasricha, A. A. Maciejewski, and H. J. Siegel, "Power and thermal-aware workload allocation in heterogeneous data centers," *IEEE Transactions on Computers*, vol. 64, no. 2. pp. 477–491, 2015.

[36] H. T. Minh and M. Samejima, "An evaluation of job scheduling based on distributed energy generation in decentralized data centers," *2015 IEEE International Conference on Systems, Man, and Cybernetics*. Kowloon, pp. 1172–1177, 2015.

[37] H. Kobayashi and B. L. Mark, *System modeling and analysis: foundations of system performance evaluation*. Prentice Hall Press, 2009.

[38] L. Minas and B. Ellison, *Energy efficiency for information technology: how to reduce power consumption in servers and data centers*. Intel Press, 2009.

[39] *Datacom equipment power trends and cooling applications*, 2nd ed. Atlanta, GA: American Society of Heating Refrigerating and Air-Conditioning Engineers (ASHRAE), 2012.

[40] ASHRAE Technical Committee 9.9, "2011 thermal guidelines for data processing environments – Expanded data center classes and usage guidance," 2011.

[41] ASHRAE, "ASHRAE handbook: fundamentals (SI)," 2001.

[42] D. Moss, "Guidelines for assessing power and cooling requirements in the data center." Dell Power Solutions, pp. 62–65, 2005.

[43] ASHRAE Technical Committee 9.9, "Data center power equipment thermal guidelines and best practices. White paper," 2016.

[44] APC, "Why do I need precision air conditioning? White paper," 2001.

[45] Emerson Network Power, "Precision versus comfort cooling. Choosing a cooling system to support business-critical IT environments. White paper," 2010.

[46] C. D. Patel, R. K. Sharma, C. E. Bash, and M. Beitelmal, "Energy flow in the information technology stack: coefficient of performance of the ensemble and its impact on the total cost of ownership," Hewlett-Packard Development Company, 2006.

[47] "2016 standard for performance rating of computer and data processing room air conditioners," Air Conditioning Heating and Refrigeration Institute AHRI 1360, 2016.

[48] "Method of testing for rating computer and data processing room unitary air conditioners," ANSI/ASHRAE Standard 127-2012, 2012.

[49] U.S. Department of Energy, "DOE's Compliance certification database," 2018. [Online]. Available: https://www.regulations.doe.gov/certification-data/CCMS-4-Air_Conditioners_and_Heat_Pumps_-_Computer_Room_Air_Conditioners.html . [Accessed: 10-May-2019].

[50] J. Moore, J. Chase, P. Ranganathan, and R. Sharma, "Making scheduling 'cool': temperature-aware workload placement in data centers," *USENIX Annual Technical Conference*. Anaheim, CA, pp. 61–74, 2005.

[51] Ernest Orlando Lawrence Berkeley National Laboratory, "Data center profiler (DC Pro) tool: user's manual," 2016.

[52] Integral Group, "'DC Pro' data center on-line profiling tool. Calculation reference manual," 2014.

[53] "Laboratory methods of testing fans for aerodynamic performance rating," ANSI/AMCA Standard 210. ANSI/ASHRAE Standard 51, 1999.

[54] M. Levy and D. Raviv, "A novel framework for data center metrics using a multidimensional approach," *15th LACCEI International Multi-Conference for Engineering, Education, and Technology: Global Partnerships for Development and Engineering Education*. Boca Raton, FL, 2017.

[55] M. Levy and D. Raviv, "An overview of data center metrics and a novel approach for a new family of metrics," *Advances in Science, Technology and Engineering Systems Journal*, vol. 3, no. 2. pp. 238–251, 2018.

[56] M. Levy and J. O. Hallstrom, "A new approach to data center infrastructure monitoring and management (DCIMM)," *2017 IEEE 7th Annual Computing and Communication Workshop and Conference (CCWC)*. Las Vegas, NV, 2017.

[57] M. Levy and J. O. Hallstrom, "A reliable, non-invasive approach to data center monitoring and management," *Advances in Science, Technology and Engineering Systems Journal*, vol. 2, no. 3. pp. 1577–1584, 2017.

[58] J. Koomey and J. Stanley, "The science of measurement: improving data center performance with continuous monitoring and measurement of site infrastructure," 2009.

[59] The Green Grid, "PUE™: A comprehensive examination of the metric. White paper # 49," 2012.

[60] ASHRAE Technical Committee 9.9, "Data center networking equipment – Issues and best practices," 2012.

[61] ASHRAE Technical Committee 9.9, "Data center storage equipment – Thermal guidelines, issues, and best practices," 2015.

[62] Dell Inc., "Dell EMC PowerEdge R740. Installation and service manual," 2018.

[63] Dell Inc., "Dell EMC PowerEdge R940xa. Installation and service manual," 2019.

[64] Dell Inc., "Dell Enterprise Infrastructure Planning Tool." [Online]. Available: http://dell-ui-eipt.azurewebsites.net/#/. [Accessed: 10-May-2019].

[65] Dell Inc., "Enterprise infrastructure planning tool user guide," 2018.