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Development of a simple power consumption model of information technology (IT) equipment for building simulation

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Abstract

The IT equipment power consumption estimated by building simulation software is much higher than the actual case, but there are no simple solutions for building engineers to reduce the bias in data center models in building simulation. This paper address this issue by proposing a simple model of IT equipment load. The model estimates the IT equipment load based on critical control inputs of the IT equipment such as its processor utilization rate and on/off status, and a survey of literature for the ordinary values of these IT equipment control variables is conducted to facilitate its uses by building engineers. A case study was conducted with building models of large offices with lots of IT equipment, and the estimated annual building energy use was reduced by more than 30% in all three cases. This shows that the conventional constant thermal load model overestimates the IT equipment load and the IT equipment model improves the accuracy of modeling of data centers in building simulation by modeling the changes of the load with the status of the servers.

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Keywords: Data center; Building simulation; IT equipment; Modeling

1. Introduction

Data center energy consumption has been on the rise in recent years. In 2010, their electricity consumption is around 1.3% of the total electricity consumption of the world [1], and their energy consumption can be tripled from 2010 to 2020 if their energy efficiency remains at the 2010 level [2]. Since the top two energy consumers in data centers are

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its information technology (IT) equipment and cooling systems [3, 4], technologies to reduce energy use of these two components in data centers are being developed rapidly in recent years [5, 6, 7].

Nomenclature

η	Percentage of active servers
μ	Average utilization rate [dimensionless]
n	Number of data points in SPECpower_ssj® 2008 database
P	Power consumption [W]
θ	Percentage of nominal power consumption
u	Utilization rate [dimensionless]

Subscript

cpu	Processor
full	Full capacity
idle	Idle
IT	IT equipment
server	Server

However, standard building simulation tools for building design have not been well configured for data center studies. Uses of building simulation software for data center studies either assumes constant power consumption density per unit area for its IT equipment or uses actual building data in the data center [8, 9]. However, both methods cannot account for their effects to the building performance effectively at the building design stage because the power consumption of the IT equipment in data centers is highly dependent on the on/off status of its servers and the utilization rate of the processors inside the servers [4, 10]. While some emerging models for building simulation software do not have these issues, they require much more understanding or performance data of the IT equipment beyond their specifications and are difficult to be used by ordinary building engineers [11, 12].

This paper addresses this issue by developing a simple model to adjust the power consumption model of IT equipment in building simulation software based on the status of the IT equipment. Common power consumption models of servers are investigated to create the adjustment model with ordinary values of the status for building designers to use the model. The results of the models are evaluated by simulations of typical office buildings to examine the importance of the model to explain the building performance.

2. Literature review on simple thermal models of server racks

Only a small portion of IT equipment models can be applied to common building simulation software [4]. These models can be categorized into two main types: constant thermal load density models and utilization-based models.

2.1. Constant thermal load density model

The assumption that the power consumption of the IT equipment per unit area is a constant is widely used in building simulation software. The model includes the power consumption of the processors, server fans, memory, uninterrupted power system (UPS), etc.. Their values are tabulated in Table 1 [9].

Table 1. Constant thermal load densities used in building simulation software

Year of construction	Core data center (space full of server racks)	Server racks in a computer room
Before 2014	646 W/m^2	232 W/m^2
After 2014	484 W/m^2	215 W/m^2

While the model is simple to apply, they do not vary with the design of data centers [6] and may easily lead to oversizing of cooling equipment. From the study of Mitchell-Jackson et al. [13], the power consumption load density of IT equipment in an actual data center can be much lower than that in Table 1. The real power consumption of the IT equipment changes with a variety of variables such as processor utilization rate and on/off status of the servers inside a data center and should not be assumed to be a constant. Hence a more realistic thermal load model is needed.

2.2. Utilization-based models

Servers operate with lots of components such as processors, memory, data storage and network equipment. Their power consumption depends on the utilization rate of the components. Alan et al. proposes a power consumption model of a server to account for the effect of utilization rates of all the components on the server power consumption [14]. But some authors find it to be too complex and suggest a simpler model as Equation (1) [15].

$$P_{server} = P_{idle} + \left(P_{full} - P_{idle}\right)u_{cpu} \quad (1)$$

The idle and full power consumption of servers in Equation (1) can be easily obtained from the specification of the servers. Others recommend adding some empirical polynomials based on indoor air temperature or heat transfer model with air flowing in the server to increase the accuracy of the model [11, 12, 16].

However, all utilization-based models only estimate the power consumption of one server among all different servers in a data center. Despite the simplicity of the equations, the model is still too complex for building designers to use in building simulation software.

3. Model development

To develop a thermal model that does not have the issues of the aforementioned models, a simple model should be developed to achieve the followings.

- The model should output a multiplier to adjust the power consumption and thermal load of an existing IT equipment model based on its average utilization rate and the on/off status of its servers;
- The model should not involve empirical coefficients that can only be estimated by extra testing.

The proposed model is developed from the utilization-based model as shown in Equation (2).

$$\theta_{IT} = \eta\left(\theta_{idle}\left(1 - \mu_{cpu}\right) + \mu_{cpu}\right) \quad (2)$$

where θ_{IT} is the multiplier of the estimated power consumption of the IT equipment in a data center in a building simulation to account for the effect of processor utilization and server on/off on the IT equipment power consumption; η is the percentage of active servers in a data center; θ_{idle} is the relative power consumption of servers at their idle state; μ_{cpu} is the average utilization rate of the processors inside a data center.

To use the model in Equation (2), η, μ_{cpu} and θ_{idle} are needed. When being monitored in real-time, η and μ_{cpu} are time-variant variables and actual measured percentage of active servers and utilization rates can be used for optimal data center control [6]. Hence Equation (2) does not need any safety factors for η and μ_{cpu}. They can also be obtained from the IT equipment engineers by engineering judgement for designs. To facilitate others to use the model without the IT expertises, reasonable values of these variables are obtained from surveying data in the literature as discussed in the following subsections.

3.1. Estimation of the percentage of active servers in a typical data center

Kaplan et al. [17] and Koomey and Taylor [18] estimated that there are 30% inactive servers in data centers based on observations from 24,000 servers, and η in Equation (8) can be assumed to be 70% if no additional evidence is provided.

3.2. Estimation of the average processor utilization rate in a typical data center

According to the summary of NRDC [19] and Shehabi et al. [2], the utilization rate of the processors of typical data centers changes with the scale of the data center and the floor area of the data center as shown in Table 2.

Table 2. Constant thermal load densities used in building simulation software

Scale of data center	Floor area of the data center	μ_{cpu}	Range of μ_{cpu}
Server room in a building	Less than 90 m^2	10%	5% to 25%
Data centers serving one organization	Between 90m^2 and 1800m^2	30%	7% to 60%
Cloud data centers serving multiple organizations	Above 1800m^2	40%	7% to 70%

If the engineers do not have evidence on μ_{cpu} in Equation (2), the scale of the data center and its floor area can be used to estimate the average and distribution of μ_{cpu} as shown in Table 2.

3.3. Estimation of the relative power consumption at idle state

To obtain θ_{idle} in Equation (2), the power consumption data of 479 servers from 2007 to 2016 in [20] are used. It includes the total power consumption of various components of a server such as processors, memory, fan, etc.. They are measured under air temperature around 20 to 25°C at various processor utilization level. The power consumption at 0% utilization rate is the idle power consumption of a server, and the power consumption at 100% utilization rate is the power consumption of a server at its full capacity.

The percentage of power consumption at idle state in Equation (2) can be calculated from the data by Equation (3).

$$\theta_{idle} = \frac{1}{n}\left(\sum_{i}^{n} \frac{P_{idle,i}}{P_{full,i}}\right) \tag{3}$$

The values of θ_{idle} sorted by the publication year of the power consumption data are shown in Table 3.

Table 3. Percentage of IT equipment power consumption at idle state categorized by the publication year of the data in SPEC2008

Year	Number of valid data points	θ_{idle}	Year	Number of valid data points	θ_{idle}
2007	12	0.630	2012	123	0.248
2008	49	0.585	2013	29	0.280
2009	70	0.453	2014	6	0.338
2010	80	0.315	2015	15	0.202
2011	76	0.366	2016	19	0.194
Overall	479	0.351			

Table 3 shows that θ_{idle} on average is 0.351 and the idle power consumption of newer servers becomes much smaller than their full power consumption. This is caused by the change of IT equipment technologies in the recent years, and the engineers should use different values of θ_{idle} according to the construction dates of the data center. If the manufacturing year is unknown or varies significantly between equipment, the average value 0.351 should be used.

To examine how accurate the estimation of θ_{idle} in Table 3 is for individual servers, the residuals of the estimation of θ_{idle} of individual servers using the values in Table 3 are plotted as shown in Figure 1.

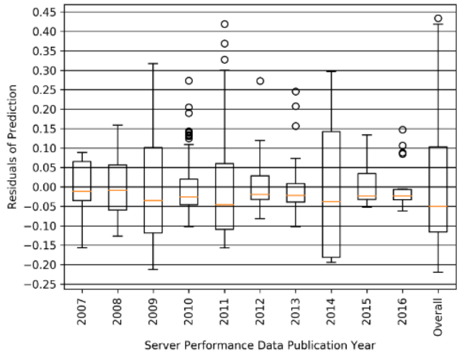

Fig. 1. Box plot of residuals of estimation of θ_{idle} for individual servers

Figure 1 shows that θ_{idle} of servers in 2010, 2012, 2013, 2015 and 2016 are estimated accurately with residuals ±0.15 within the estimated value. However, θ_{idle} in the other years does not exhibit the same behavior. The reason may be due to the rapid development of the technologies to reduce server idle power consumption during these years. Hence the change of idle power consumption in a year becomes too large to be represented by a single value.

4. Case study by building simulation

To demonstrate the use of the IT equipment model, the model in Equation (2) is applied to a model of three typical large office buildings with data centers, and their simulation results are compared to the original results to examine the difference of the building performance with the adjustment of the IT equipment load. The building models come from the 2013 commercial prototype building models of typical large offices in [9, 21]. They simulate the performance of a large office building under three different climates where cooling dominates as tabulated in Table 4.

Table 4. Climate of the locations where the large office buildings are situated

Location	Climate
Miami, Florida, U.S.A.	Very hot and humid
Phoenix, Arizona, U.S.A.	Hot and dry
San Francisco, California, U.S.A.	Mixed and marine

Each large office has a floor area of 46,300m^2. Their core data centers are situated at their basement. Each data center has a floor area of 780m^2 with an IT equipment load density at 484W/m2 while the each of the 12 IT closets have a floor area 31m^2 with an IT load density at 215 W/m^2. Its building materials, windows, lighting equipment, etc. are in compliance with ASHRAR Standard 90.1-2013 [22]. Their cooling is supported by two water-cooled chillers for general office area, one water-to-air heat pump for the basement data center and three water-to-air heat pumps with a total cooling capacity. Other details of the building model can be found in [9, 21].

To apply the model in Equation (2) to the building model, θ_{IT} of the basement data center and the IT closets is calculated by the values of η, θ_{idle} and μ_{cpu} chosen according to the aforementioned criteria. η and μ_{cpu} are assumed to be time-invariant in this case because IT equipment status varies with the applications of the data centers. The choices of the values are tabulated in Table 5.

Table 5. Choice of inputs to Equation (2) for the basement data center and the IT closets in the large office building model

Location	η	θ_{idle}	μ_{cpu}	θ_{IT}
Basement data center	70%	0.28	30%	0.3472
IT closets	70%	0.28	10%	0.2464

θ_{IT} calculated from Table 4 is applied to the building models. The simulations were conducted using EnergyPlus v8.6 [16] with the typical meteorological year weather data, and the results are shown in Table 6.

Table 6. Percentage changes of the building performance after applying Equation (2) with information from Table 5.

Location	Annual building electricity consumption	Annual cooling equipment electricity consumption	Annual IT equipment energy consumption
Miami, Florida, U.S.A.	-33.0%	-22.2%	-67.3%
Phoenix, Arizona, U.S.A.	-34.3%	-23.8%	-67.3%
San Francisco, California, U.S.A.	-37.0%	-24.5%	-67.3%

Table 6 shows how important it is to model the data center energy consumption with variables such as processor utilization rate. By incorporating the effect of control variables to the IT equipment load, the estimation of the annual electricity consumption of the building is lowered by more than 30% and becomes more realistic than the original constant load model.

5. Conclusions and future work

To conclude, a simple power consumption model that adjusts the IT equipment power consumption in a building simulation software is introduced. It adjusts the power consumption based on realistic operation of the IT equipment such as processor utilization rate and the idle states of servers and helps to reduce the overestimation of IT equipment load in building simulations as verified with three building models in different climates. In the future, the model will be validated by using operation data of a server room to examine how accurate it is relative to the constant load model.

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