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Improving data center energy efficiency using a cyber-physical systems approach: integration of building information modeling and wireless sensor networks

Wei Wu[a]*, Wenjia Li[b], Deify Law[a], Woonki Na[a]

[a]*California State University, Fresno,5241 N. Maple Ave., Fresno, CA 93740, USA*
[b]*New York Institute of Technology, 1855 Broadway, New York, NY 10023, USA*

Abstract

The increase in data center operating costs is driving innovation to improve their energy efficiency. Previous research has investigated computational and physical control intervention strategies to alleviate the competition between energy consumption and thermal performance in data center operation. This study contributes to the body of knowledge by proposing a cyber-physical systems (CPS) approach to innovatively integrate building information modeling (BIM) and wireless sensor networks (WSN). In the proposed framework, wireless sensors are deployed strategically to monitor thermal performance parameters in response to runtime server load distribution. Sensor data are collected and contextualized in reference to the building information model that captures the geometric and functional characteristics of the data center, which will be used as inputs of continuous simulations aiming to predict real-time thermal performance of server working environment. Comparing the simulation results against historical performance data via machine learning and data mining, facility managers can quickly pinpoint thermal hot zones and actuate intervention procedures to improve energy efficiency. This BIM-WSN integration also facilitates smarter power management by capping runtime power demand within peak power capacity of data centers and alerting power outage emergencies. This paper lays out the BIM-WSN integration framework, explains the working mechanism, and discusses the feasibility of implementation in future work.

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Keywords: Data center; energy efficiency; building information modeling; wireless sensor network; cyber-physical systems

* Corresponding author. Tel.: +1-559-278-6011; fax: +1-559-278-4475.
E-mail address: weiwu@csufresno.edu

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1. Introduction

Data centers in the United States consumed about 76 billion kilowatt-hours in 2010, equivalent to 2% of all electricity used in the country that year [1], which is also estimated to grow at 12% per year [2]. In 2012, the power costs for the data center equipment over its useful life exceed the cost of the original capital investment. By 2020, the carbon footprint of data centers is expected to exceed the airline industry [3]. The rising data center energy consumption and rising energy costs have elevated the importance of data center energy efficiency as a strategy to reduce costs, manage capacity and promote environmental responsibility. Nevertheless, data center energy efficiency (defined as the ratio of useful computation to total source energy) is notoriously low, estimated at 15% or less [4]. A considerable portion of the energy cost of running a data center, however, is avoidable through an intelligent understanding and management of the cyber-physical [5, 6] interactions within them. Substantial savings can be attained by efficiently designing the physical environment [7]. A framework is needed to create a unique merger between the physical infrastructure and resource management functions of the cluster operating system to take a holistic view of data center energy management [8].

To accomplish this goal, real-time server environment information such as temperature needs to be monitored. The conventional way of completing this task is via temperature data from the internal thermometers of the machines [8]. This has many drawbacks and limitations, one being that the location of the temperature reading from inside the machine is inconsistent from model to model. Current solution to this problem has been to install external temperature sensors, yet this method also has several deficiencies. First, these sensors are expensive. Second, these sensors are often permanently installed or built into devices, which leads to a lack of flexibility and contextual information. The proliferation of wireless sensor networks (WSN) offers a viable alternative for the underlying network infrastructure. Therefore, this paper considers data centers as cyber-physical systems (CPS), and proposes the integration and coordination of virtual models and the physical infrastructure to simulate and control energy efficiency. The CPS approach bridges the cyber layer (e.g. information, communication and intelligence) with the physical layer (e.g. servers, CRAC units, and building structures) through the use of WSN.

Integration of a WSN with an existing data center building management system (BMS) has a number of advantages including cheaper and faster installation, which allows increased number of sensors deployed to gain more fine-grained measurements and control, and the associated flexibility of the temporary infrastructure deployment needed to perform measurements in a limited time [9]. Before deploying the WSN, a representation of the physical and service environment of data center is needed in order to accurately predict signal propagation and as a result, link quality between nodes. This can be easily attained through building information modeling (BIM). BIM is a new business paradigm in capital projects that emphasizes integrative practices in project planning, design, construction and operation with unprecedented computational support from advanced information modeling applications. BIM provides a robust platform that facilitates the creation and sharing of physical and functional characteristics of a building facility as well as the business intelligence among stakeholders spanning its lifecycle. Recent market research suggests that BIM is gaining ubiquitous acceptance and implementation across the global architectural, engineering, construction and facility management (AEC-FM) industry.

2. Related works

In the proposed CPS approach to integrate BIM and WSN in data center energy modeling and control, a key assumption is that critical technology that enables such integration is readily available and well documented in literature. The following paragraphs reviewed scholar research in the areas of data center thermal simulation and its interaction with server load balancing; sensor-based thermal monitoring and energy management; BIM integration in thermal simulation and real-time performance management; machine learning and data mining in energy performance predication and optimization, and data center power management. It is understood that conversation, meaning the exchange of a large amount of heterogeneous data, needs to take place among these interrelated domains and computational frameworks, which will eventually dictates the feasibility of such a highly integrated framework as proposed in this study.

2.1. Computational Fluid Dynamic (CFD) model for data center energy management

Early work on energy minimization for data centers focused on computational fluid dynamic (CFD) models to analyze and design server racks and data center configurations to optimize the delivery of cold air, and thereby minimize cooling costs [7]. There are an increasing number of papers on the CFD simulations of thermal profile of a data center in recent years. Schmidt et al. [10] compared CFD modeling results with thermal measurements for data center and the comparison is generally satisfactory except some rack thermal profiles deviated from measurements. Regions that exceeded the equipment inlet air temperature specifications by a significant amount were also reported [10]. VanGilder and Lee [11] presented a technique which allows data center designer or operator to achieve any desired partitioning of available airflow among the floor tiles of a raised-floor data center without resorting to trial-and-error with the CFD simulations. Providing the efficiency and quality of current CFD simulation practices, its workflow tends to be independent and isolated from the overall facility design and configuration process using BIM. The promise held by BIM is to provide a comprehensive information reservoir that captures all physical and functional data of a facility at scalable levels of details, including the geometric and system information required in the CFD analysis. Yet there is a lack of protocol for data extraction from BIM as direct inputs to proprietary CFD simulation software applications. Some open information exchange standards such as Industry Foundation Classes (IFC) has been tested in fulfilling the role but such as practices remain as individual cases.

2.2. Load-balancing policies for data center energy efficiency

Subsequent research focused on the development of optimal load-balancing policies, at both the server and rack levels. Constraints on these policies were either the minimum allowed computational performance or the maximum allowed peak power consumption [12, 13]. Some recent papers considered policies to minimize the total data center energy consumption by distributing the workload in a temperature-aware manner [14]. Research on load distribution based on the thermal state of the data center led to the development of fast and accurate estimation techniques to determine the temperature distribution in a data center, based on sparsely distributed temperature measurements [8]. Approaches to the data center energy management problem based on queuing theory and Markov decision processes can be found in [15]. In contrast, very few studies [16] considered the dynamics and synergies between the computational workload and the cooling performance of the data center. Meanwhile, outcomes of these studies were usually presented in a complex and mathematical manner, which made them difficult to understand for corporate owners and data center operators.

2.3. WSN in thermal monitoring and management

Research on use of sensors and sensor networks for monitoring rack temperature for a safe and reliable data center can be found in [8, 17 and 18]. WSN is typically integrated in existing BMS. Ambient data collected through carefully deployed environmental sensors provide insights in operational thermal performance in data centers, which help identify potential hot zones as well as characterize the thermal profile. More importantly, sensor data can be accumulated and analyzed with data mining and machine learning techniques to study time- and load- sensitive patterns of thermal performance in data centers, and become valuable basis for predicting temperature distribution and developing interference strategies to proactively tackle potential service interruption due to overheat.

2.4. Building information modeling integration with real time thermal management

There is a lack of scholarly publication on BIM for data center energy efficiency simulation and its possible concurrent use with sensing technology such as WSN to provide an integrated solution to data center thermal performance, energy efficiency and power management. Nevertheless, several studies, e.g. [19, 20, 21], investigated the feasibility and methodology to integrate BIM with wireless environmental sensors for real-time thermal monitoring and power management in regular buildings, which may be transferrable to data center scenarios.

2.5. Machine learning and data mining techniques for building energy management

Various data mining and machine learning techniques have been used for building energy management. For instance, [22] proposed a multi-modal sensor agent platform that is non-intrusive and low-cost, combining information such as motion detection, CO_2 reading, sound level, ambient light, and door state sensing, and this platform aims to decrease the energy usage of HVAC systems in various building applications. Actual test bed deployment demonstrates that these sensor agents can be used to accurately estimate the number of occupants in each room using machine learning techniques, and that these techniques can also be applied to predict future occupancy by creating agent models of the occupants. These predictions will then be used by control agents to enable the HVAC system increase its efficiency by continuously adapting to occupancy forecasts of each room. In [23], an energy efficient building design process is developed using data mining technology, which can extract interrelationships and patterns of interest from a large dataset that contains information from various sources such as the building location, envelope, HVAC system, lighting, controls, and equipment. In [24], data mining techniques that are capable of integrating any thermal comfort standards and indoor daylight procedures is used to learn from the vast amount of building sensor data, observe correlations between weather conditions, building characteristics and low-energy comfortable rooms, and build models that optimize occupants' comfort, energy consumption and management and the interrelationship among them. In [25], several machine learning algorithms, including linear regression, neural networks, and Support Vector Machine (SVM) algorithm, are applied to and evaluated on a new residential data set that contains sensor measurements collected every 15 min, with the objective of determining which techniques are most successful for predicting next hour residential building consumption. In [26], the authors studied how to use SVM algorithm to predict building energy consumption in the tropical region, whereas [27] apply SVM algorithm to predict hourly building cooling load. C4.5 classification algorithm is proposed in [28], an improvement of the well-known decision tree algorithm [29], to analyze the combination of internal and external ambient conditions. The mining algorithms are used to determine comfort constraints and the influence of external conditions on a building's internal user comfort.

3. Preliminary study: WSN data consistency with CFD simulation

In this section, we conduct a consistency check between CFD simulation data and measured data through WSN in a previous study conducted [18]. The goal is to build the confidence in WSN-based data collection. ANSYS FLUENT, a commercial CFD solution, is used to simulate the temperature distributions inside a server's hot box. The preliminary CFD results will be compared with the experiments at Nodes 6, 7, and 8 of the Georgia Southern University Student Data Center conducted by Bazemore and Li [18] as shown in Fig. 1.

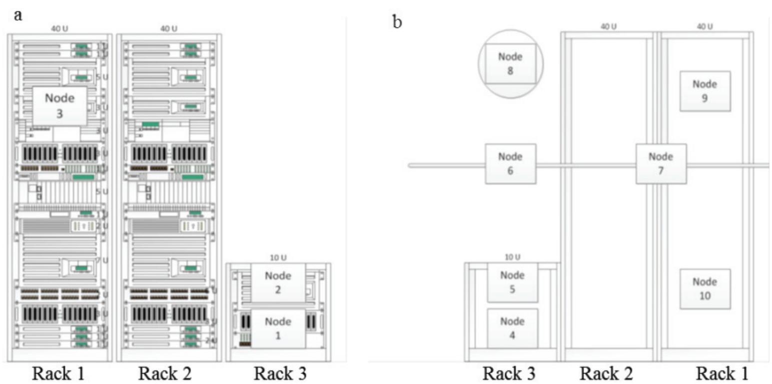

Fig. 1. Schematic of the rack group: (a) front of the rack group and (b) back of the rack group [18].

Nodes 1 and 2 were placed on the front of Rack 3 whereas Node 3 was placed on the front of Rack 1. Nodes 4, 5, 9, and 10 were placed on the back sides of the racks. Nodes 6 and 7 are located in the back middle of the hot box to measure the ambient temperature whereas Node 8 is placed in the hot box air exhaust. To perform the CFD simulations, the geometry of server hot box is modeled in a three-dimensional system as shown in Fig. 2. The back surface of Rack 1 is set approximately to the average temperature of Nodes 9 and 10 according to [18] at 308.9 K whereas the back surface of Rack 3 is set approximately to the average temperature of Nodes 4 and 5 at 303.4 K. The ambient temperature is set to 301.2 K and air speed of hot box air exhaust is set at approximately 1.7 mile/hour.

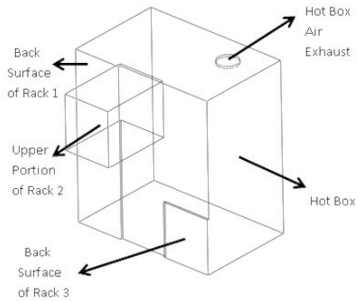

Fig. 2. Schematic of a hot box for CFD simulations.

Table 1 demonstrates satisfactory agreements between the preliminary CFD simulation results and the wireless sensor experiments for average temperature readings at Nodes 6, 7 and 8. Both measured and simulated temperatures at Node 7 were observed to be slightly higher than Node 6 due to the closer proximity of the higher temperature generated from Rack 1.

Table 1. CFD simulation results in comparison with sensor data for average temperature readings at Nodes 6, 7, and 8.

Node	Average Temperature (*K, Wireless Sensor*)	Average Temperature (*K, CFD Simulation*)
6	303.7	302.6
7	304.8	304.3
8	303.7	302.0

In addition, Fig. 3 presents the three-dimensional simulated temperature contour plot for the hot box region. Fig. 3 suggests that a majority of thermal energy propagates from the back surface of Rack 1 to the hot box domain in which the high thermal energy is eventually dissipated to the ambient condition.

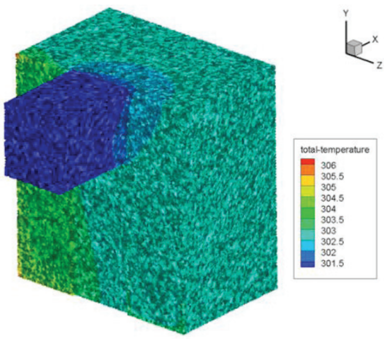

Fig. 3. Three-dimensional simulated temperature (in K) contour plot for the hot box region.

4. Data center power management

In this section, a traditional power management technique of a centralized uninterruptible power supply (UPS) based data centers is reviewed, and a power management strategy that can communicate through our common BMS with BIM and WSN is proposed.

The power system of a typical data center is based on a standard AC utility feeder [30]. Two independent utility feeders can be used to further increase power reliability of the data centers. Specifically, a UPS can deal with peak load during a short period of time (1~2 hours) [31]. For a long period of peak power, it is less effective due to the battery used by most of the energy within 2 hours. Thus, many data centers have been employing distributed per-server batteries, or distributed UPS architectures where individual machines have their own UPS in order to shave the peak power, thereby eliminating a potential failure of a specific server [31]. In a typical UPS, there are three components including AC/DC rectifier, the battery, and the DC/AC inverter, which suggests that AC/DC/AC double power conversion is always required to feed the AC loads. This double power conversion in a centralized UPS design is leading up to 35% energy loss, so a distributed UPS can feed power to the corresponding server directly without using this double power conversion. Each server rack could have a distributed UPS that can be charged and discharged throughout a DC distribution power network in Fig. 4. As a result, the efficiency can be increased up to 35% and save cost by avoiding this AC/DC power conversion [32].

By using this DC distribution with distributed UPSs, it may be able to reduce power distribution losses by up to 50% compared to the AC distribution system because AC/DC power conversion loss is much bigger than that of DC/DC power conversion. Also grid tie inverter concept has been studied to increase the battery life of the UPS system [33]. Grid-tie inverters can help the battery life of the UPS by converting DC energy generated from renewable sources into AC grid and feeding it into the grid, that allows not only excess DC energy to be fed back to the grid, but can be used with UPS in a grid-interactive manner for local storages and emergency response. Grid-tie system includes a unidirectional DC/DC converter from the renewable energy sources, and DC/AC inverter with energy storages with a bidirectional DC/DC converter for charging and discharging purposes. Interactive control would be desired by coordinating with these power electronics converters, DC/DC converters, and DC/AC inverter with UPSs. In terms of the unidirectional DC/DC converter connected to renewable energy sources, Maximum Power Point Tracking algorithm (MPPT) would be normally used for the optimal control in the most of renewable energy industries. Moreover, with the use of the proposed dual-scenario BIM/WSN framework explained in the following section, it is able to keep monitoring the power of the power usage in each server, so the dynamic peak power shaving can be achieved with a minimum time delay, saving the energy cost compared to using of the static peak power shaving [34].

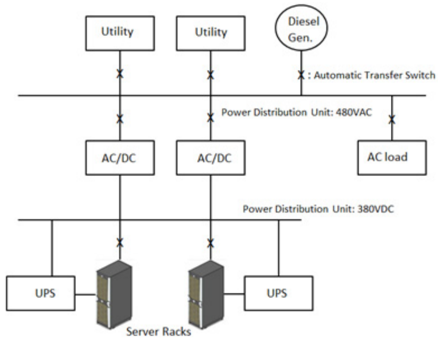

Fig. 4. DC power distribution system with distributed UPSs.

5. Proposed framework

In developing the framework, we consider two scenarios: 1) direct intervention in potential system failure scenario; and 2) mitigation and alternative design scenario. In a simple fashion, the proposed framework is illustrated in Fig. 5. The data center is represented in BIM, which contains all geometry, thermal property, and function information, including all building systems and server layout. WSN is deployed to monitor the real-time thermal performance of the data center at room, rack, and individual server levels. With allowable performance tolerance defined by operators and patterns learned through the data mining/machine learning agent system, the WSN can conduct ongoing analysis and diagnosis of thermal performance against such tolerance, and actuate potential direct intervention of the HVAC system through the communication with the BMS.

In the other scenario, when abnormal thermal behavior has been detected, the owner or facility manager may choose the mitigation approach to explore potential design strategies to improve thermal performance and energy efficiency. Desired data center information can be extracted from BIM as input into dedicated thermal and energy simulation programs to conduct analysis. The generated simulation results will be compared with measured performance data to determine the improvements. Such exercise can go on for as many rounds as needed until the owner and facility managers are satisfied with the simulation results. Due to the parametric modeling capacity, different design options could be tested in BIM in a rapidly and financially affordable way.

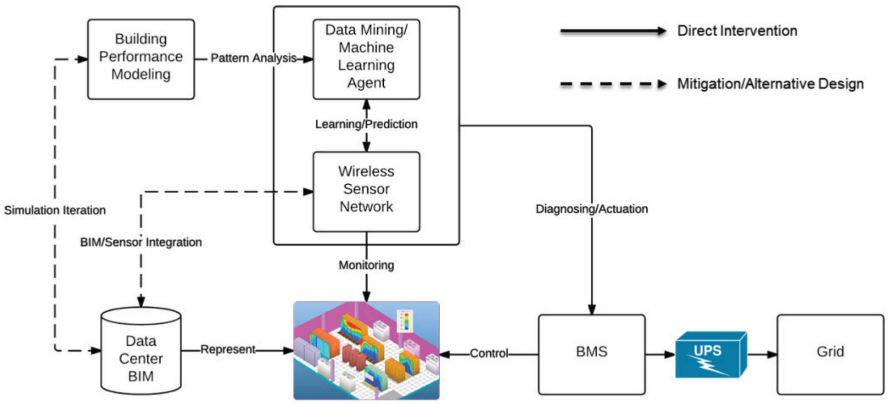

Fig. 5. Proposed dual-scenario BIM-WSN framework.

6. Discussion and future work

In this paper, we reviewed current research on data center thermal performance and energy efficiency. Despite advancements in simulation algorithm and software programs, there is a lack of integrated framework to provide data center owners and facility managers with insights into real-time monitoring and intervention in a timely and financially affordable manner. Proliferation in BIM and WSN offers a great promise to this issue. We proposed a simplistic framework to explore the potential of a CPS approach by integrating BIM and WSN for more robust solutions to improve data center thermal performance and energy efficiency. Future research will focus on framework development, creating use cases, and conducting case studies to collect empirical data.

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