Prototype Energy Models for Data Centers

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Prototype Energy Models for Data Centers

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ABSTRACT
Data centers in the United States consume about two percent of the nation’s electricity. Because heat gains from IT equipment drive cooling demand, data centers offer unique opportunities for energy savings. However, no prototype energy model for data centers is available in the suite of existing U.S. Department of Energy’s Commercial Prototype Building Models. This study presented the development of two new data center prototype models and their implementation in OpenStudio and EnergyPlus. The small-size data center model represents a computer room in a building served by computer room air conditioners (CRACs); while the large-sized model represents stand-alone data centers served by computer room air handlers (CRAHs) with a central chiller plant. For each data center model, two levels of IT equipment (ITE) load density were considered, to cover the wide range of IT power density of data centers: 40 and 100 W/ft² (430 and 1,076 W/m²) for the computer room, and 100 and 500 W/ft² (1,076 and 5,382 W/m²) for the stand-alone data center. All other assumptions, such as building envelope, lighting, HVAC efficiencies and schedules, were based on the minimal requirements of ASHRAE Standard 90.1 at various vintages. We introduced a novel concept of supply and return air approach temperatures to capture the essential effects of non-uniform airflow and temperature distribution in data centers. The approach temperatures were pre-computed by computational fluid dynamics (CFD) simulations for various configurations of ITE loads and airflow containment management in data centers. A new feature was developed in EnergyPlus to implement the approach temperature method. A case study was conducted to demonstrate the use of the data center models. The two data center models cover all U.S. climate zones and can be used to evaluate energy saving measures for data centers, as well as to support development of data center energy efficiency codes and standards.

Keywords: data center; EnergyPlus; energy efficiency; prototype energy model; approach temperature; OpenStudio
1. Introduction

A data center is a unique building type within the building sector, due to its energy intensive characteristics. Data centers in the United States consumed about 2 percent of the nation’s electricity in 2014 and that level is expected to continue to increase in the near future [1]. The IT equipment (ITE) and its associated heating, ventilation and air conditioning (HVAC) systems are the predominant energy consumers in data centers [2]. The ITE results in a much more intensive cooling load than typical equipment in commercial facilities such as office buildings. Previous research has demonstrated significant energy saving potential on both the ITE side [3] and the HVAC system side [4–7]. With more aggressive adoption of energy efficiency strategies, the energy demand of data centers is projected to decrease by 45 percent compared to the current efficiency trends [1]. Therefore, it is critical that building designers and energy modelers are able to evaluate energy benefits of different design strategies and energy efficiency technologies for data centers. However, while much effort has been made to model ITE energy use (especially CPU power) accurately, few modeling efforts are targeted at the entire data center energy consumption, which should capture the interaction between ITE and HVAC systems in particular [8]. Methodologies and computational tools need to be developed to enable interactive, holistic modeling of ITE and HVAC systems.

The internal loads in data centers are fairly constant over the course of a year and are distributed non-uniformly, depending on the arrangement of server racks. This leads to a non-uniform distribution of airflow and temperature in data centers. The airflow and temperature fields are significantly influenced by the airflow containment management scheme, e.g., cold aisle containment, hot aisle containment, and fully open [9,10]. As the ITE power, indoor air distribution, and HVAC equipment performance interact with each other, it is challenging to model the entire data center holistically. Particularly, it is challenging to capture both the ITE and HVAC energy consumption as well as the realistic air distribution within data centers simultaneously.

Potentially, this analysis can be achieved by integrating building energy modeling (BEM) tools with computational fluid dynamics (CFD) tools. However, BEM and CFD tools serve different purposes and have distinct fundamental assumptions [11,12], which makes it difficult to connect the two. More specifically, BEM is generally based on the nodal model, which treats the building components as a node with homogeneous characteristics (e.g., assuming a well-mixed room air temperature), while CFD can provide a much more detailed description of thermal performance and indoor airflow patterns rather than a single node. BEM programs usually run at a timestep of 5 to 60 minutes for an entire year to simulate the energy performance of all the zones in a building, considering dynamics of outdoor weather conditions, indoor heat gains, and HVAC equipment. Conversely, CFD programs usually run at a smaller timestep (i.e., milliseconds to seconds for a few hours or days) to simulate the non-uniform airflow and temperature fields of a single zone in a building, under a limited number of static design and operating conditions. This mismatch in spatial and temporal resolutions leads to a unique challenge when attempting to couple the BEM and CFD modeling programs.

Many researchers have explored methodologies for coupling energy modeling tools with CFD tools to solve the uneven air distribution issue and improve simulation accuracy [13,14]. These methods have been used in applications such as modeling naturally ventilated buildings [15,16], displacement ventilation systems [17], and others [13,18]. The fast fluid dynamics (FFD) method has also been adopted by Tian et al. [19,20] to simulate the air distribution within the floor plenum and whitespace of data centers. However, it should be noted that the state-of-the-art coupling of energy modeling and CFD/FFD tools requires multidisciplinary knowledge and expertise, therefore, it is still limited to research, and not widely adopted by general users. There is a strong need for
simple yet comprehensive modeling tools that allow general users to evaluate the energy performance of different designs and technologies for data centers.

Prototype building energy models are of great significance because they are the starting point in conducting analyses for various applications, such as building energy saving potential analysis, building design, building energy market evaluation, and building energy policymaking [21]. Prototype building models are supposed to represent the existing building stock, so the simulation results represent the actual energy consumption [22]. A suite of 16 building prototypes (Table 1) in 17 climate locations (across all eight U.S. climate zones, Figure 1) have been developed by the United States Department of Energy’s (USDOE’s) national laboratories. These prototypes represent 80 percent of new construction floor area in the United States [23]. These prototype building models have been widely adopted to support simulation and evaluation of energy efficiency measures for the development and compliance calculations of building energy efficiency codes and standards, such as ASHRAE Standard 90.1. These models are available in both EnergyPlus and OpenStudio model formats. They can also be generated with OpenStudio “measures” [24] using OpenStudio-Standards GEM [25], which is a Ruby library that extends the OpenStudio Software Development Kit (SDK) to implement rules defined in ASHRAE Standards 90.1, 55, and 62.1.

However, there is no prototype energy model for data centers. Such model is needed to conduct technical analyses to support technology assessment and codes and standards development, e.g., ASHRAE Standard 90.4 and ASHRAE Technical Committee 9.9. To fill this gap, we developed new data center prototype models and implemented them in OpenStudio and EnergyPlus. EnergyPlus is an open source software program that models heating, ventilation, cooling, lighting, water use, renewable energy generation, and other building energy flows, and it is the flagship building simulation engine supported by USDOE [26]. OpenStudio is a suite of free and open-source software applications for building energy analysis using EnergyPlus as the simulation engine [27]. The new prototype data center models are an addition to the existing USDOE Commercial Prototype Building Model suite [28–30].

This study made novel contributions to the field of data centers and building energy modeling: (1) an innovative concept of approach temperature was introduced to represent the essential effects of non-uniform airflow and temperature distribution in data centers, and the method was implemented in EnergyPlus, (2) the approach temperatures were pre-computed by computational fluid dynamics (CFD) simulations for various configurations of ITE loads and airflow containment management in data centers, and (3) two new prototype data center energy models, using the approach temperature method, were developed which are additions to the existing suite of 16 prototype energy models of commercial and residential buildings developed by USDOE’s national laboratories.

In this paper, Section 2 introduces the key data, assumptions, and technical approaches for developing the data center prototype models. It also discusses the CFD simulations that were performed to generate the supply and return approach temperatures under different scenarios that were needed for modeling ITE in EnergyPlus. The existing ITE object in EnergyPlus and OpenStudio was modified accordingly to accommodate the new approach. The new data center prototype models were implemented in the OpenStudio-Standards GEM and can be used by general users via the OpenStudio measure “Create DOE Prototype Building” coupled with the pre-computed approach temperatures. The above implementations are publicly available through open source code and free accessible tools, as described in Section 3. An example application was also conducted to demonstrate the prototype model capabilities discussed in Section 3. This research is further discussed in Section 4 and summarized in Section 5.
<table>
<thead>
<tr>
<th>Large Office</th>
<th>Medium Office</th>
<th>Small Office</th>
<th>Warehouse</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Large Office" /></td>
<td><img src="image" alt="Medium Office" /></td>
<td><img src="image" alt="Small Office" /></td>
<td><img src="image" alt="Warehouse" /></td>
</tr>
<tr>
<td>Stand-alone Retail</td>
<td>Strip Mall</td>
<td>Primary School</td>
<td>Secondary School</td>
</tr>
<tr>
<td><img src="image" alt="Stand-alone Retail" /></td>
<td><img src="image" alt="Strip Mall" /></td>
<td><img src="image" alt="Primary School" /></td>
<td><img src="image" alt="Secondary School" /></td>
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<td>Full Service Restaurant</td>
<td>Hospital</td>
<td>Outpatient Health Care</td>
</tr>
<tr>
<td><img src="image" alt="Quick Service Restaurant" /></td>
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<td><img src="image" alt="Hospital" /></td>
<td><img src="image" alt="Outpatient Health Care" /></td>
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<tr>
<td>Small Hotel</td>
<td>Large Hotel</td>
<td>Mid-rise Apartment</td>
<td>High-rise Apartment</td>
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<tr>
<td><img src="image" alt="Small Hotel" /></td>
<td><img src="image" alt="Large Hotel" /></td>
<td><img src="image" alt="Mid-rise Apartment" /></td>
<td><img src="image" alt="High-rise Apartment" /></td>
</tr>
</tbody>
</table>
2. Methodology

Data centers differ from conventional commercial buildings in their: (1) high internal loads from IT equipment requiring cooling year round, (2) non-uniform distribution of internal loads in data centers, depending on the layout of cold and hot aisles and arrangement of server racks, and (3) airflow containment management scheme (e.g., fully open, cold aisle containment, and hot aisle containment), which significantly influences the airflow and temperature distribution in data centers.

These unique characteristics pose a challenge when modeling data center energy use and cooling system operation. One option is to use CFD tools such as Fluent to model the airflow and heat transfer in the data center, which can capture its detailed airflow and temperature fields. However, CFD tools are computationally expensive (due to a small mesh/grid and a fine timestep of seconds); thus usually only a limited number of static design and operating conditions can be modeled. That limited number cannot be used to simulate the annual energy use of data centers, as outdoor conditions vary across the year, even if indoor thermal loads are constant or little changed. The other option is to use building energy modeling tools such as EnergyPlus to simulate the annual energy performance of the data center at an hourly or sub-hourly timestep while assuming the zone air is well mixed and uniform. However, even though EnergyPlus has room air models (e.g., underfloor air distribution, thermal displacement) that can consider stratification of air along the vertical dimension, the horizontal non-uniformity of the indoor thermal environment cannot be captured.

To address the data center modeling challenge, we developed a novel method for integrating the CFD tools and BEM tools. First, we introduced the concept of supply and return approach temperature to capture the effect of air flow mixing, bypass, and recirculation in data centers. The supply approach temperature represents the difference between the air handler unit (AHU) supply air temperature and the IT rack inlet air temperature, while the return approach temperature represents the difference between the AHU return air temperature and the IT rack outlet air temperature. These two approach temperatures depend on the IT loads and the airflow containment management in the data center. Next, the CFD tool Fluent was used to model the detailed airflow and thermal field of the data center, and to calculate these two approach temperatures, which are
compiled as look-up tables for later use. Then, the two approach temperatures were implemented in EnergyPlus to enable the annual simulation of the data center while capturing the non-uniformity of the data center using the pre-computed two approach temperatures. Finally, the new feature of EnergyPlus was adopted in the OpenStudio-Standards GEM to enable the creation of the prototype energy models for data centers.

2.1 Supply and Return Approach Temperatures

The ITE and the HVAC system are the two predominant energy consumers in data centers. The total power of the ITE is the sum of the server rack power and the server fan power. Both are directly related to the CPU load ratio. Sahini [31] found by experiments that the server inlet air temperature also has a significant impact on the server rack power and server fan speed. Based on Sahini’s experimental results, we derived the performance curves of the server power and server fan air flow rate, which are inputs for the prototype models in EnergyPlus.

For the HVAC system, the most important and challenging part is the simulation of the air-side energy consumption due to the non-uniform air distribution within data centers (Figure 2). An existing ITE object in EnergyPlus can simulate the ITE power, as well as the air-side energy use. However, it does not fully consider different air distribution scenarios within data centers from two perspectives. First, on the supply air side, the existing ITE object considers the possibility of recirculation but no bypass, which is common in data centers. Second, on the return air side, the return air temperature is simplified as the routine EnergyPlus “well-mixed” zone temperature, which does not represent the realistic thermal behavior of the data center due to air distribution. Therefore, it is necessary to enhance the existing EnergyPlus ITE object.

We reviewed the existing metrics that describe air distribution in data centers [32], such as the Rack Cooling Index (RCI) and Return Temperature Index (RTI) introduced by Herrlin [33,34], Air Distribution Index (ADI) and Air Mixing Index (AMI) proposed by Qian et al. [35], Air Distribution Effectiveness (ADE) proposed by Zhang et al. [36], and negative pressure ratio, bypass ratio, recirculation ratio, etc., proposed by Tozer et al. [37]. The RCI and RTI metrics work well to evaluate the air management effectiveness of data centers, but are not suitable for energy simulation. The ADI, AMI, ADE, and bypass/recirculation ratios can be used to evaluate air mixing and performance of the integrated heat transfer based on exergy analysis, but cannot accurately assess the thermal environment of the data center. In this case, we proposed two new metrics—the supply approach temperature and the return approach temperature—for use in the simulation of air-side energy consumption. They refer to the temperature difference of IT equipment inlet and outlet from AHU supply and return temperature, respectively. The calculations of the two approach temperatures are shown in equations 1 and 2:

\[ \Delta T_{supply} = T_{in} - T_{supply} \] (1)

\[ \Delta T_{return} = T_{return} - T_{out} \] (2)

Where,

\( \Delta T_{supply}, \Delta T_{return} \) are the supply and return approach temperatures

\( T_{in}, T_{out} \) are the ITE inlet and outlet air temperatures

\( T_{supply}, T_{return} \) are the supply and return air temperatures of the air handler unit
Figure 2. Traditional air distribution in data centers [38]

Figure 3 shows the overall calculation logic of the AHU airflow for the ITE object in EnergyPlus.

First, the ITE inlet air temperature is calculated using design AHU supply air temperature and supply approach temperature. Second, two performance curves, Curve 1 and Curve 2, are used to calculate the CPU power and ITE fan flow rate, respectively, based on ITE inlet air temperature.
and CPU load ratio. The IT server fan power is calculated from the fan flow rate using Curve 3. The total AHU cooling load is the sum of the CPU power, IT server fan power, and uninterruptible power supply (UPS) power. The UPS equipment is assumed to be located within the data center room if any.

The ITE outlet air temperature is calculated in equations 3 and 4 by Sang-Woo Ham [39] based on the first law:

\[
T_{\text{server, out}} = T_{\text{server, in}} + \frac{P_{\text{server}}}{c_{\text{air}} \rho_{\text{air}} V_{\text{fan}}} 
\]

\[
P_{\text{server}} = P_{\text{IT}} + P_{\text{fan}}
\]

Where,

\( T_{\text{server, out}} \) and \( T_{\text{server, in}} \) are the inlet and outlet air temperatures of the IT server

\( P_{\text{server}} \) is the total power of the IT server

\( V_{\text{fan}} \) is the server fan flow rate

\( P_{\text{IT}} \) is the power of the IT racks

\( P_{\text{fan}} \) is the server fan power

Third, the AHU return air temperature is calculated using the ITE outlet air temperature and the return approach temperature. Finally, the AHU air flow rate is calculated from the total AHU cooling load, the AHU supply air temperature, and the AHU return air temperature. Then the performance curve of the AHU fan was used to calculate the fraction of full load AHU power based on flow fraction, which is the AHU air flow rate divided by its maximum air flow rate. The AHU fan performance curve was from ASHRAE 90.1 Performance Rating Method. EnergyPlus can then accurately simulate the air-side energy use of the data centers.

For a data center, single constant values or scheduled values of the supply and return approach temperatures are used based on the load ratio and configuration of the data center. However, the supply and return approach temperatures are computed from detailed CFD simulation results by aggregating the spatially distributed temperatures.

### 2.2 Key Model Assumptions

All the detailed assumptions were documented in the scorecard of the prototype model, which will be released in 2020 together with a new version of OpenStudio. In this paper, we introduce key data and assumptions, including building geometry and size, ITE load density, HVAC systems, envelope, and internal loads.

By physical floor area and cooling capacity, data centers were generally segmented into five categories: server closet, server room, localized data center, mid-tier data center, and enterprise-class data center. Table 2 shows the statistical properties of each data center type [40,41]. Smaller size data centers tend to be physically located within a building, while larger size data centers tend to be stand-alone. In this case, we defined two representative data center types: (1) small-size, representing data centers that are located within a building, covering server closets, server rooms, and localized data centers, and (2) large-size, representing stand-alone data centers, covering localized data centers, mid-tier data centers, and enterprise-class data centers.

The assumptions of size and ITE load density were based on the statistical data listed in Table 2 and discussion with data center experts and stakeholders. We assumed 600 square feet (ft²)
(55.7 square meters [m²]) and 6,000 ft² (557.4 m²) as the typical sizes of the small and large data centers, respectively. Considering the wide range of power density, we assumed two levels of ITE load density for each data center size. For the small data centers, the density was either 40 or 100 watts per square foot (W/ft²) (430 or 1,076 watts per square meter [W/m²]), while the density was either 100 or 500 W/ft² (1,076 or 5,382 W/m²) for the large data centers. Table 3 lists the key assumptions.

Table 2. U.S. data centers characteristics by type [40]

<table>
<thead>
<tr>
<th></th>
<th>Area range (ft²)</th>
<th>Number of servers installed</th>
<th>Number of data centers by type (k)</th>
<th>Data center area by type (kft²)</th>
<th>Average servers per location</th>
<th>Average area per data center (ft²)</th>
<th>Kilo-watts per rack **</th>
<th>Average density (W/ft²) *</th>
</tr>
</thead>
<tbody>
<tr>
<td>Server closet</td>
<td>&lt;100</td>
<td>&lt;5</td>
<td>1,150</td>
<td>1</td>
<td>77</td>
<td>5</td>
<td>65</td>
<td></td>
</tr>
<tr>
<td>Server room</td>
<td>100–999</td>
<td>5–25</td>
<td>1,026</td>
<td>2</td>
<td>201</td>
<td>5</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Localized data center</td>
<td>500–1,999</td>
<td>25–100</td>
<td>64</td>
<td>26</td>
<td>573</td>
<td>5</td>
<td>227</td>
<td></td>
</tr>
<tr>
<td>Mid-tier data center</td>
<td>2,000–19,999</td>
<td>100–500</td>
<td>9</td>
<td>161</td>
<td>3,326</td>
<td>10</td>
<td>484</td>
<td></td>
</tr>
<tr>
<td>Enterprise-class data center</td>
<td>&gt;20,000</td>
<td>500–1,000+</td>
<td>6</td>
<td>85</td>
<td>491</td>
<td>13,648</td>
<td>15</td>
<td>540</td>
</tr>
</tbody>
</table>

*Note: Calculated values.

**Note: Kilowatts (kW) per server is an assumption. The standard for power density of older servers was in the range of 4–5 kW per rack, while newer servers vary from 8–10 kW per rack in the low range to an average of 15–16 kW per rack, and even more ambitious servers go above 20 kW per rack [42]. Large size data centers tend to have higher-performance newer servers.

Table 3. Key assumptions of data center prototype models

<table>
<thead>
<tr>
<th></th>
<th>Small Data Center (computer room in a building)</th>
<th>Large Data Center (stand-alone building)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size, in ft² (m²)</td>
<td>600 (55.7)</td>
<td>6,000 (557.4)</td>
</tr>
<tr>
<td>Physical location</td>
<td>Located within a building</td>
<td>Stand-alone</td>
</tr>
<tr>
<td>Envelope</td>
<td>Adiabatic</td>
<td>ASHRAE 90.1, varies with climate zones</td>
</tr>
<tr>
<td>IT load density, in W/ft² (W/m²)</td>
<td>40 or 100 (430 or 1,076)</td>
<td>100 or 500 (1,076 or 5,382)</td>
</tr>
<tr>
<td>System type</td>
<td>Computer room air conditioner (CRAC)</td>
<td>Computer room air handler (CRAH) + chilled water system Water-side economizer (Only required in ASHRAE 90.1-2013)</td>
</tr>
<tr>
<td>Supply fan</td>
<td>Variable speed</td>
<td>Variable speed</td>
</tr>
</tbody>
</table>
In terms of the HVAC system, ITE rooms can be conditioned with a wide variety of system types, including packaged computer room air-conditioning (CRAC) units and central station air-handling systems [43]. Packaged DX computer room air conditioners (commonly described as CRAC units) are the most common type of cooling equipment for smaller data centers. On the other hand, larger data centers tend to use computer room air handlers (CRAH) with larger motors and fans, which are also well suited for variable volume operation through the use of variable speed drives (VSDs) to maximize efficiency at part-load [44]. For the prototype models, we adopted CRAC units with variable-speed fans for the small data centers and CRAH with variable speed fans coupled with a chilled water system for the large data centers, so they are both able to adjust AHU supply flow rate based on CPU load. A water-side economizer is only required in ASHRAE 90.12013, and is integrated with the centralized chilled water system [45].

ITE inlet temperature is the most important parameter for ITE in terms of its reliability and performance [46]; therefore, it is the control target of data center prototype models. According to Thermal Guidelines for Data Processing Environments [46], the recommended range of the ITE inlet temperature is 18°C–27°C (64.4°F–80.6°F). In this case, the system may be considered safe and reliable as long as the ITE inlet temperature doesn’t exceed 27°C. Based on CFD simulation results in Section 2.5, the supply approach temperature can reach as high as 12.1°C under fully open air management scenario (i.e., no air containment). Conservatively, the CRAC/CRAH supply air temperature (SAT) is set as typical SAT setpoint 55°F (12.8°C). There is no air containment assumed in the prototype models. Cold-aisle and hot-aisle containment can be applied as energy efficiency measures, which can enable warmer SAT as well as warmer chilled water supply temperature.

As for humidity, the results from Wan et al. [47] showed that a data center with a low incident rate of electrostatic discharge (ESD)-induced damage operating at 25 percent relative humidity will maintain a low incident rate if the humidity is reduced to 8 percent. In this case, we adopted 8 percent as the lower limit of humidity and enabled a humidifier in the HVAC system to meet the requirement. Generally, dehumidification is needed only for outdated data centers that use old-fashioned tapes to store data, as the tapes should avoid high humidity. As there are fewer such data centers, we focused on more recent data centers for the prototype models, which work well with high humidity, so we did not specify the dehumidification requirement in the prototype models.

As small data centers are physically located within a building, the heat gain through the building envelope is minimal, assuming data centers and their adjacent zones are all conditioned areas. Therefore, the envelope of the small data centers is assumed to be adiabatic. On the other hand, large data centers are stand-alone centers, and we assumed their envelopes comply with ASHRAE Standard 90.1 requirements. All other basic assumptions such as internal loads, HVAC efficiencies, and schedules were based on ASHRAE Standard 90.1. Particularly, the ITE load schedules were modeled as a constant fraction of the peak design load per the monthly schedule illustrated in Figure 4, according to ASHRAE 90.1 Appendix G [45,48]. It should be noted that the infiltration was assumed to be zero because data centers are pressurized to avoid infiltration and to keep out unwanted contaminants such as dust [43].
2.3 CFD Simulation

The CFD software Ansys Fluent version 18.0.0 was used to simulate the airflow field and temperature field inside the data center. Fluent solves Navier-Stokes (N-S) equations with appropriate turbulent models (e.g., standard k-ε turbulent model, RNG k-ε turbulent model, and large eddy simulation model). The tool utilizes the finite volume method to solve N-S equations, which implies that the fluid domain is decomposed to many small control volumes. Based on the generated grid, the partial differential equations can be discretized into algebraic equations at each point of the grid. The calculation is conducted by means of iterating these algebraic equations until the residuals meet the convergence criteria. After the convergence of the calculation, the spatial profiles of the thermal environment and airflow patterns can be obtained. Gambit (Version 2.4.6), a pre-processing software of Fluent, was employed to build the geometric model of the data center room (Figure 5) and generate the grids for further simulation.
Figure 5. Geometry of a small data center under three layouts: (a) fully opened, (b) cold aisle containment, (c) hot aisle containment.

For this study, four types of data centers were simulated. The geometric assumptions are shown in Table 4. The full-capacity IT load of the four data center types were 24, 60, 600, and 3,000 kW. Each type of data center had three air containment management strategies: no containment (fully open), cold aisle containment, and hot aisle containment. Containment as a method of temperature control can ideally increase efficiency by separating the cold air from the warm air and keeping machines from overheating and eliminating hot spots [49]. A cold aisle containment layout encloses the cold aisle to limit the blending with exhausted warm air, creating a hot-air return “plenum” in
the data center, as shown in Figure 5(b). Conversely, a hot aisle containment layout encloses the hot-air aisle to contain the exhaust air from the IT equipment (ITE) while creating a cold-air supply “plenum”, as shown in Figure 5(c). The airflow leakage through the containment system was ignored in this simulation, but the heat conduction through the containment material was considered. The thermal conductivity of the containment material was set as 0.15 W/m*K to represent a good performance of heat insulation.

Table 4. Key geometric assumptions of data center prototype models in CFD modeling

<table>
<thead>
<tr>
<th>Model name</th>
<th>Small Data Center</th>
<th>Large Data Center</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room dimension, in feet (m)</td>
<td>30<em>20 (9</em>6)</td>
<td>100<em>60 (30</em>18)</td>
</tr>
<tr>
<td>Room height, in feet (m)</td>
<td>14 (4)</td>
<td>2.5 (0.8)</td>
</tr>
<tr>
<td>Raised floor height, in feet (m)</td>
<td>2 (0.6)</td>
<td>2.5 (0.8)</td>
</tr>
<tr>
<td>IT load density, in W/ft² (W/m²)</td>
<td>40 (430)</td>
<td>100 (1,076)</td>
</tr>
<tr>
<td>Aisle arrangement</td>
<td>7-tile pitch</td>
<td>7-tile pitch</td>
</tr>
<tr>
<td>Number of rows</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Number of racks per row</td>
<td>3</td>
<td>15</td>
</tr>
</tbody>
</table>

The total number of grids for the four data center types were 1.3 million, 1.8 million, 4.1 million, and 5.9 million. The minimum mesh volume was $9.37 \times 10^{-6}$ cubic meters (m³), located close to the IT racks. The IT racks were considered to be solid plane heat sources, where the heat is released from the top and bottom planes to the interspace between two racks. This study simulated two load ratio scenarios: 50 percent and 100 percent. The AHU system workflow was not simulated here; alternatively, a continuous supply air flow of 12.8°C (55°F) was provided under the floor and then circulated into the room through the floor tiles with holes. Two scenarios were considered in the simulation for the AHU supply air flow rate to represent different air movement situations (e.g. recirculation and bypass), 120 cubic feet per minute (cfm)/kW (0.06 m³/s/kW) and 200 cfm/kW (0.09 m³/s/kW). The supply air flow velocities for both scenarios could be calculated based on the total IT load (kW) and area of the supply air inlet (m²). Overall, 48 scenarios of different combinations of IT loads, supply air flow rates, and containment layouts were simulated.

The steady solver was employed during the calculation. As for representing the turbulence airflow caused by the ventilation, the RNG k-ε model adopted in this work was commonly employed by previous work [50–52], with the overall consideration of accuracy, computing efficiency, and affordability for modeling the indoor flow field. The differential viscosity model and the swirl dominated flow in the RNG options were selected. During the iterative process, the pressure-implicit with splitting of operators (PISO) algorithm was employed to solve the pressure-velocity coupling equations. The second-order upwind scheme was also used to consider the diffusion-convection in the governing equation. The calculation was computed in a four-node Linux cluster, and each node of the cluster had 12 processors (2.4 GHz Intel). The total computing time for one case was 15 minutes.
2.4 Server airflow and power sensitivity

For calculating the real IT load under each specific setting, the efficiency factors of the CPU power and the IT equipment fan power were considered. We referred to two sets of empirical fitted curves to describe the efficiency factors, i.e., CPU power ratio and ITE fan air flow ratio under different ITE inlet temperatures and load ratios [31]. They correspond to Curve 1 and Curve 2 in Figure 3, respectively. In EnergyPlus accordingly, the ITE object takes input of total watts/m^2, then uses “Design fan power input fraction” to divide up the total into CPU and ITE power. The ITE object calculates the design ITE fan air flow rate by multiplying the “Design Fan Air Flow Rate per Power Input” with ITE fan rated power. Curve 1 is used to adjust CPU power based on CPU load ratio and ITE inlet temperature. Curve 2 is used to adjust ITE air flow based on CPU load ratio and ITE inlet temperature.

As shown in Figure 6(a), the CPU power was only slightly influenced by the ITE inlet temperature, which indicated that the CPU power equals the full-capacity IT load multiplied by the load ratio. However, as shown in Figure 6(b), the influence of ITE inlet temperature on the ITE fan air flow rate was significant. Assuming ITE fan power varies proportionally with ITE fan air flow rate, i.e., Curve 3 in Figure 3 is simplified as linear, the ITE fan power was also significantly impacted by ITE inlet temperature. Therefore, we implemented the curves in the simulation to better calculate the fan power based on different load ratios and ITE inlet temperatures.

![Figure 6. (a) fitted curve of CPU power ratio and (b) fitted curve of ITE fan air flow ratio under different ITE inlet temperature and load ratios](image)

Based on engineering rule-of-thumb [38,53,54], the fan of a data center server is generally designed with a temperature increase of 20°F between the inlet and outlet of the ITE rack. We set the fan pressure value accordingly to achieve the standard temperature increase for the fully-opened scenario. Further based on the fitted curve of ITE fan air flow ratio under different ITE inlet temperature and load ratios in Figure 6, we calculated the adjusted fan air flow velocity for the other two scenarios, and adjusted the fan pressure setting in the CFD simulation accordingly. Therefore, we can simulate the varying flow for different scenarios of containment styles and supply air flow rates.

2.5 Results of CFD parametric studies

As previously mentioned, there are 48 modeling scenarios with different sets of IT loads, supply air flow rates, and containment layouts. For each scenario, we calculated the area-averaged temperature of four spots: the supply temperature of the room, ITE inlet temperature, ITE outlet temperature, and the return temperature of the room, as illustrated in Figure 7. As described in equations 1 and 2, the supply approach temperature is calculated using the supply air temperature and the ITE inlet air temperature, while the return approach temperature is calculated using the ITE
outlet air temperature and the return air temperature. We generated a look-up table (Table 5) to query the supply and return approach temperature under different geometric and load settings.

Figure 7. Diagram of four spots for calculating the supply and return approach temperature for hot aisle containment
Table 5. Look-up table for the supply and return approach temperatures

<table>
<thead>
<tr>
<th>Scenario #</th>
<th>Total IT load [kW]</th>
<th>Containment/IT</th>
<th>Load ratio</th>
<th>Supply air flow rate [cfm/kW]</th>
<th>Temperature [°C]</th>
<th>SI Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Open</td>
<td>Cold</td>
<td>Hot</td>
<td>50%</td>
<td>100%</td>
</tr>
<tr>
<td>1</td>
<td>24</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>12.8</td>
<td>75.1</td>
</tr>
<tr>
<td>2</td>
<td>24</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>12.8</td>
<td>72.4</td>
</tr>
<tr>
<td>3</td>
<td>24</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>12.8</td>
<td>74.4</td>
</tr>
<tr>
<td>4</td>
<td>24</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>12.8</td>
<td>71.6</td>
</tr>
<tr>
<td>5</td>
<td>24</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>12.8</td>
<td>70.0</td>
</tr>
<tr>
<td>6</td>
<td>24</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>12.8</td>
<td>55.4</td>
</tr>
<tr>
<td>7</td>
<td>24</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>12.8</td>
<td>59.3</td>
</tr>
<tr>
<td>8</td>
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<td>12.8</td>
<td>51.3</td>
</tr>
<tr>
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<td>24</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>12.8</td>
<td>51.4</td>
</tr>
<tr>
<td>10</td>
<td>24</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>12.8</td>
<td>57.1</td>
</tr>
<tr>
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<td>x</td>
<td>12.8</td>
<td>20.9</td>
</tr>
<tr>
<td>12</td>
<td>24</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>12.8</td>
<td>16.6</td>
</tr>
</tbody>
</table>

Different equipment layouts and supply air flow rates significantly influence the indoor airflow pattern and thus the temperature distribution. Figure 8 shows the air velocity field of the small-size data center under different layouts (a: fully open, b: cold aisle containment, c: hot aisle containment) when the IT load ratio is 100 percent and the supply air flow rate is 200 cfm/kW (0.094 m³/s/kW).
Figure 8. The air velocity field of the small-size data center under different layouts (a: fully open, b: cold aisle containment, c: hot aisle containment), with an IT load ratio of 100 percent and supply air flow rate of 200 cfm/kW (0.094 m³/s/kW)

The aisle containments constrain the supply airflow and ITE outlet airflow in the cold aisle containment layout and the hot aisle containment layout, respectively, which successfully separates the cool air from the exhausted warm air. There are two advantages in the airflow patterns of the latter two layouts: (1) the cold supply air can be fully used to cool the IT rack without a bypass circulation directly to the return outlet, and (2) without the blending of the exhausted warm air from the IT rack, the ITE inlet temperature remains lower, which yields a lower fan power and total heat gain (Figure 6(b)).
Figure 9 shows the temperature distribution of the small-size data center under different layouts (a: fully open, b: cold aisle containment, and c: hot aisle containment) when the IT load ratio is 100 percent and the supply air flow rate is 200 cfm/kW (0.09 m³/s/kW).

The supply air temperature remained at 12.8°C for each layout. The inlet and outlet temperature of both the IT racks and return air temperature for the cold aisle containment scenario were lower than they were for the other layouts, which yielded a relatively lower supply and return approach temperature. Similarly, the hot aisle containment layout largely leveraged the cool supply air for cooling the IT equipment and reduced the mixing of hot air with cool air. A fully open layout caused the highest supply and return approach temperatures, as well as the highest return air temperature. This is because without separating the cool supply air from the exhausted warm air, the higher ITE inlet temperature will increase the fan power, which increases the total heat gain inside the room.
Figures 10 and 11 show the temperature distributions and air velocity fields under different supply air flow rates, when the IT load ratio is 100 percent and without containment. By comparing the return air temperature under 120 cfm/kW (0.06 m³/s/kW) and 200 cfm/kW (0.09 m³/s/kW) air flow rates, it shows that increasing the supply air flow rate will significantly cool the entire environment to a lower temperature. However, a higher supply air velocity causes more cool air bypass than a lower velocity does, which leads to a higher portion of the cool air not being used, thus less effective cool air distribution.

**Figure 10.** The temperature distribution of the small-size data center under different supply air flow rate (a: 120 cfm/kW (0.06 m³/s/kW), b: 200 cfm/kW (0.09 m³/s/kW)), with an IT load ratio of 100 percent and fully opened.
3. Implementation and Applications

We implemented the aforementioned enhancements to the existing ITE object in EnergyPlus and OpenStudio. The modifications were published in EnergyPlus version 8.9, released in March 2018, and also in OpenStudio version 2.8.0, released in April 2019. The new data center prototype models were implemented in the OpenStudio-Standards GEM and can be used by general users via the OpenStudio measure “Create DOE Prototype Building.” These models and tools are available to the public. An example application was conducted to demonstrate the capabilities of the prototype data center models.

3.1 Implementation of the new ITE object in EnergyPlus

The enhancements to the ITE object introduce a new air flow calculation method, Flow Control with Approach Temperatures, to represent the air flow management (air bypass, recirculation, and mixing) of data centers for the purpose of energy calculation. Specifically, the implementation assumes that the ITE inlet temperature differs from the AHU supply air temperature, and that the actual AHU return air temperature differs from the regular return air temperature when the zone is assumed to be well-mixed in EnergyPlus.

The new method applies this concept of temperature differences to calculate the actual AHU supply air temperature and zone return air temperature as functions of the ITE inlet and outlet temperatures, based on Equation 1 and Equation 2. Two fields—supply approach temperature and return
approach temperature—were added to the ITE object in EnergyPlus to represent the deviation. Each approach temperature can be input as a constant value or a time-series schedule for simulation. The two approach temperatures (or temperature schedules) can be calculated by CFD tools for typical IT load levels and air flow management or provided by measurement data or lookup tables, and these external calculations can then be imported into EnergyPlus using this new ITE object.

Correspondingly, when the new method is applied during the sizing and simulation (since the actual return temperature of the AHU is overwritten by the ITE outlet temperature with approach temperature adjustment), the supply air mass flow rate of the AHU is calculated as in Equation 5:

\[ m_{sys} = \frac{Q_{sys}}{c_{air} \ (T_{(sys, in)} - T_{(sys, out)})} \] (5)

Where,

- \( m_{sys} \) is the AHU supply air flow rate (kg/s)
- \( Q_{sys} \) is the total AHU cooling load (W)
- \( c_{air} \) is the specific heat of air (J/kg.K)
- \( T_{(sys, in)} \) is the weighted return air temperature from all ITE objects in the zone (°C)
- \( T_{(sys, out)} \) is the designed supply air temperature to the ITE objects (°C)

In particular, in zones with ITE objects, to allow the zone heat balance to converge in EnergyPlus, the well-mixed zone temperature is not controlled by applying the thermostat setpoint control logic, since the actual controlled object is the supply air temperature. When using this method, the user input of zone cooling setpoints are ignored and the unmet hour for cooling does not apply for the ITE zones. Meanwhile, the ITE CPU and fan power could vary considerably with the ITE inlet temperature, which is determined by user input performance curves. During system sizing, the maximum ITE inlet temperature and according ITE CPU and fan power considering performance curves and approach temperature has to be used for calculations instead of the design ITE inlet temperature, to avoid under-sizing.

3.2 Implementation of the data center prototype models in the OpenStudio-Standards GEM

The improved ITE object in EnergyPlus was adopted in OpenStudio SDK, and the data center models were implemented through the OpenStudio-Standards GEM, which is a Ruby library and an extension of the OpenStudio SDK. It compiles ASHRAE standards and streamlines the process of creating the USDOE prototype buildings in OpenStudio format [55]. OpenStudio models are more flexible than EnergyPlus models, and they can be transformed automatically using OpenStudio “measures.” A measure is one of the most powerful features of the OpenStudio platform. It is a scripting facility that can be used to apply energy conservation measures to models to create reports and visualizations, and even to sew together custom workflows [24]. Having the prototype building models available in OpenStudio will enable users to easily perform thorough, portfolio-scale impact analyses of a large number of energy conservation measures.

The OpenStudio-Standards GEM is the foundation of the OpenStudio measure “Create DOE Prototype Building.” That measure takes three arguments: (1) ASHRAE commercial building type (e.g., Medium Office, Full Service Restaurant), (2) ASHRAE climate zone (e.g., 1A-Miami, FL, 3C-San Francisco, CA), and (3) ASHRAE Standard 90.1 version (e.g., 2004, 2010)—and creates an OpenStudio version of the corresponding commercial building prototype model. Figure 12
shows the interface of the OpenStudio App while applying the measure. The two types of data center prototype models were implemented in this GEM and enabled in the measure. For each data center type, two levels of ITE load density are considered to represent the lower and higher end of typical IT load range.

### 3.3 Applications

The data center prototype models can be used to: (1) evaluate energy performance of different designs and technologies for data centers, (2) provide technical analyses to support technology assessment and codes and standards development, such as ASHRAE Standard 90.4 and ASHRAE Technical Committee 9.9 on Mission Critical Facilities, Data Centers, Technology Spaces and Electronic Equipment, (3) perform portfolio-scale impact analysis of a large number of energy conservation measures, and (4) support energy policymaking for the data center industry.

The prototype models can be automatically generated using two approaches. One approach is for general users to download the OpenStudio measure “Create DOE Prototype Building” from the Building Component Library [56] and apply the measure to an empty model in OpenStudio App, which is a graphical user interface (Figure 12). The other is for advanced users with programming skills to download the source code of the OpenStudio-Standards GEM, and write Ruby code to invoke the function.

![Figure 12. Screenshot of applying the OpenStudio measure “Create DOE Prototype Building” in the OpenStudio App](image)
3.3.1 Case Study

A simulation case study was conducted to demonstrate the application of the data center prototype models for evaluating the energy performance of different air containment management schemes. The following steps describe the workflow for using the prototype models for simulation and analysis:

1. Generate the four data center prototype models (two sizes and two ITE load densities) in three U.S. climate zones (1A, 3C, and 5A) and two vintages (2004 and 2013). The selected three climate zones are typical in the U.S., representing hot and humid, mild, and hot summer and cold winter, respectively. The selected two vintages represent efficiency levels of older and newer data center designs.

2. Find the supply and return approach temperatures under the three air containment scenarios in the lookup table generated by CFD simulations, based on the CRAC/CRAH design air flow rate and CPU load ratios.

3. Expand the models generated in Step 1 to cover three air containment scenarios, by applying the approach temperatures accordingly. Thus, the total number of simulations is, 4 data center prototypes * 3 climate zones * 2 vintages * 3 air containment scenarios = 72.

4. Run the simulations and analyze the results.

Figure 13 shows the simulated energy use intensity (EUI) of the four data center prototype models under different scenarios. Overall, the EUI under the same air containment scenario stayed fairly consistent among different vintages and climate zones, regardless of data center size and ITE load density. This is reasonable and expected since the ITE load was the monopolistic source of heat gains within data centers. The EUI of data centers in climate zone 1A are marginally higher than those in climate zone 3C and 5A, mainly because the outside temperature in 1A is the highest, which leads to certain efficiency loss on the heat rejection side of the HVAC system. The EUI of small data centers decreases slightly from 2004 to 2013 due to HVAC equipment efficiency improvement. However, this is not always the case for large data centers. Since ASHRAE 90.1-2013, water-side economizers are mandatory for chilled water based cooling system, which can save chillers’ energy use. On the other hand, water-side economizers need larger condenser water flow rate, which boosts the energy use of pumps and cooling towers. Therefore, the overall performance is a combined result from these components.

Compared with the fully open air management scenario, the cold aisle containment is able to achieve 6 to 8 percent of the total energy savings, and the hot aisle containment is able to achieve 5 to 7 percent savings. The energy savings come from two sources: (1) more efficient operation of CPU and ITE fans due to the lower ITE inlet air temperature, and (2) reduced cooling energy use due to lower cooling load, which mainly consists of DX coil energy use (for small data center) and chiller energy use (for large data center). This result is in line with engineering rule-of-thumb. However, it should be noted that the purpose of this case study is to demonstrate potential applications of the data center prototype models, rather than assessment of real data centers. The actual energy performance of a specific data center with air containment would depend on many factors, including the physical arrangement of server racks, the control logics of the cooling system, and the air tightness of the containment [57,58].

In this case study, the CRAC/CRAH supply air temperature (SAT) is assumed to be the same at 12.8°C across different air management scenarios. However, benefitting from cold or hot aisle containment, the ITE inlet air temperature can be improved, which enables a higher SAT and return air temperature (RAT). The benefit of a higher RAT to the cooling unit is better heat exchange across the cooling coil, increased cooling capacity, and overall higher efficiency. On the other hand, if a water-side economizer was installed in the cooling system, a higher SAT would allow a higher chilled water temperature, unlocking more opportunities for free cooling that
reduces the number of hours of chiller operation, thus reducing energy use. It is a trending retrofit strategy to deploy cold/hot aisle containment together with a control logic that integrates both a higher SAT and a water-side economizer. In future research, this could be implemented as an OpenStudio measure, to further explore the comprehensive energy saving potentials of air containment management schemes.

Figure 13. EUI comparison between different data center prototype models under four air containment scenarios: (a) a large-size data center with high ITE load density, (b) a large-size data center with low ITE load density, (c) a small-size data center with high ITE load density, and (d) a small-size data center with low ITE load density.

Cooling loads due to building envelope heat transfer is traditionally assumed to be much less than the IT loads and thus often ignored. In this case study, we quantified the impact of modeling envelope loads in data centers. According to Section 2.2, the envelope of small data centers is assumed to be adiabatic while the envelope of large data centers is assumed to comply with ASHRAE 90.1 standard, so we used large data centers for this analysis.

Figure 14 illustrates the percentage of envelope loads in the total loads at peak hour across different vintages, IT power densities, and climate zones. We found: (1) Envelope loads generally account for no more than 1% in total loads, the percentage drops to even lower than 0.2% when the IT power density is high; (2) The percentage gets lower with higher performance envelope (e.g. from 2004 standards to 2013 standards), milder climate, and higher IT power density. In summary, the impact of envelope loads in data centers is very limited based on the simulation results, so it is reasonable to ignore envelope loads while analyzing data center performance.
4. Discussion

The approach temperatures are the key input parameters for data center energy simulation. They mainly vary with the air management effectiveness of the data center and air distribution scenarios (e.g., bypass or recirculation). In other words, two factors (1) whether a data center is cold-aisle contained, hot-aisle contained, or fully open, and (2) whether the supply air will bypass or recirculate the ITE—will significantly influence the approach temperatures. The prototype models are not supposed to represent all air distribution scenarios or an “average” situation, but are intended to provide available options for users to apply on specific cases. It should be noted that the generated look-up table for the approach temperatures from CFD modeling are only applicable to the traditional room-based cooling architecture, which supplies cold air through a raised floor. Newer data center cooling architectures such as row-based cooling or server rack cooling are not modeled in our CFD simulations. However, the approach temperature method can still be applicable as long as appropriate inputs are used for the specific architecture.

Currently, users input the supply and return air approach temperatures as constant values or schedules of predefined values to EnergyPlus models (IDF files). This is a limitation; in reality the approach temperatures may vary with the actual dynamic IT loads that cannot be predicted. For data center applications that require full CFD simulations or strong coupling of energy models with CFD simulations, e.g., the rear-door heat exchangers used in high-density data centers, the proposed approach temperature based models might not be a good fit.

The monthly ITE load schedule (Figure 4) is meant to represent the diversity of load ratio to cover different operational conditions across various seasons of the year, rather than to represent the potentially significant different operating loads of real data centers. In this case, the simulated energy usage of the prototype models may not match that of real data centers, however, it can be used to compare the energy performance of different design strategies and technologies to support energy efficient design of data centers. Important future work includes validation of the CFD computed approach temperatures with actual measurement of data centers with various configurations. Liquid cooling is becoming a key technology for data centers with larger IT loads. There is a need for future model development of liquid cooling type data centers.
5. Conclusion

Two new prototype data center energy models were developed to support technology assessment for energy efficient design of data centers as well as data centers energy codes and standards (e.g., ASHRAE Standard 90.4) development. These energy models cover a small-size computer room served by CRACs in a building, and a large-sized stand-alone data center served by CRAHs with a chiller plant. For each data center type, two levels of ITE load density were considered, to represent the lower and higher ends of the typical IT load range. All U.S. climate zones are covered in the data center models which require different energy efficiency levels for the data center envelope, lighting, and HVAC systems.

A novel concept of supply and return air approach temperatures was introduced to capture the effects of non-uniform airflow and temperature distributions in data centers. Computational fluid dynamics models were used to compute the approach temperatures for various configurations of IT loads and airflow management in data centers. These pre-computed approach temperatures were implemented as lookup tables. An enhancement was made to EnergyPlus to enable the use of the approach temperature method to model data centers. The developed data center models were released as open source code as part of the OpenStudio Standards GEM.

The simulation-based case study, using the developed prototype energy models of data centers, show, compared with the fully open air management scenario, the cold aisle containment can save 6 to 8 percent of the total energy, while the hot aisle containment can save 5 to 7 percent energy. These savings are consistent across data center sizes, vintages, and climate zones.

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