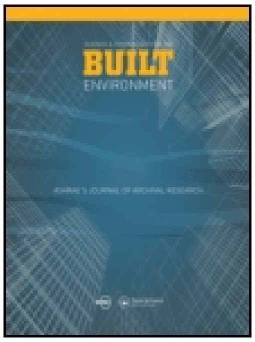

Science and Technology for the Built Environment

ISSN: 2374-4731 (Print) 2374-474X (Online) Journal homepage: http://www.tandfonline.com/loi/uhvc21

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To cite this article: Weilin Li & Peng Xu (2016) A fast method to predict the demand response peak load reductions of commercial buildings, Science and Technology for the Built Environment, 22:6, 633-642, DOI: 10.1080/23744731.2016.1145533

To link to this article: http://dx.doi.org/10.1080/23744731.2016.1145533

Accepted author version posted online: 22 Feb 2016.
Published online: 22 Feb 2016.

Science and Technology for the Built Environment (2016) **22**, 633–642
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ISSN: 2374-4731 print / 2374-474X online
DOI: 10.1080/23744731.2016.1145533

A fast method to predict the demand response peak load reductions of commercial buildings

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Demand response has become an increasingly important part of building control. However, before building owners and operators agree to participate in demand response programs with utility companies, knowledge of the maximum peak load that can be shifted in their buildings, as well as the economic benefits, is required. Engineers need to be able to predict the peak load reductions before control strategies are implemented. A good way to overcome difficulties in the prediction is via building performance simulations, but modeling a large commercial building in detail requires significant efforts and becomes very complicated. In demand response simulations, the accuracy of the peak load reduction is more important than the full-year energy performance. Therefore, this research proposes a facile simulation method for the accurate prediction of peak load reductions. This novel method is built on the basis of EnergyPlus with many simplifications and defaults. The principles of these simplifications and defaults are explained through thermal balance analysis, and the accuracy of the new demand response prediction method is verified through a case study completed in California.

Introduction

In recent years, demand response (DR) has become an important part of the electricity market, especially in commercial buildings. DR refers to tariffs or programs designed to motivate end-use customers by responding to changes in the price or availability of electricity over time by changing their normal patterns of electricity use. It can also be defined as incentive payment programs to reduce the usage of electricity when grid reliability is jeopardized (U.S. Department of Energy, 2006). In commercial buildings where energy consumption due to air-conditioning is the main part of the peak load, the most commonly used DR method is to shift the air-conditioning load from peak to off-peak hours by resetting the zone temperatures. The cooling load can be shifted due to thermal mass effects of buildings. Feasible DR strategies for HVAC systems were summarized by Motegi et al. (2007), in which global temperate adjustment and passive thermal mass storage were introduced in detail. Many studies have shown that resetting the temperatures of buildings can shift the peak loads of air-conditioning systems (Xu et al. 2004; Lee and Braun 2008a, 2008b, 2008c). Some researchers have presented different methods to determine the temperature set-points for different control objectives. Lee and Braun (2008b) developed a simple approach to estimate building zone temperature set-point variations to minimize peak cooling demands. The method used in their research employed simple inverse building models, and analytical solutions from the models can determine set-point trajectories. Sun et al. (2010) adjusted the indoor room temperature set-point to restrain the daily peak demand for a given threshold to reduce the monthly electricity cost via a proportional-integral-derivative (PID) algorithm. Ma et al. (2012) developed an economic model predictive control (MPC) technique, where the MPC framework, zone temperature, and power models were used to reduce energy and demand costs of air-conditioning systems.

However, in field tests and experiments, the shift in the peak load ranges from 3%–50% of the peak, depending on the building and the HVAC system type (Braun 1990; Andresen and Brandemuehl 1992; Snyder and Newell 1990; Rabl and Norford 1991). For example, Conniff (1991) conducted some experiments to analyze the potential of using the thermal mass of the building for peak load reduction and concluded that the peak load reduction was only approximately 3%. Meanwhile, other researchers have demonstrated that the load reduction can range from 10%–30% and is economically acceptable (Ruud et al. 1990; Keeney and Braun 1997). Xu and Haves (2009) conducted tests on two commercial buildings with different thermal masses, that is, a heavy mass and a light mass, and concluded that pre-cooling and demand shed strategies worked well in both types of buildings. Compared to the normal peak load, these strategies reduced the cooling load by 25%–35% for a light building, and an exponential temperature adjustment strategy reduced the cooling load by 30% for a heavy building. Therefore, there is a need for building owners and operators to estimate the potential in the peak load reductions before signing DR agreements with utility companies.

Received June 23, 2015; accepted December 20, 2015
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On the other hand, for a given building, control strategies need to be optimized because each building has a different mass level and a different mechanical system. Because conducting experiments in occupied commercial buildings is difficult, simulations are a natural way to optimize the control strategies and calculate the savings. Differing from experiments, simulations can be carried out before any tests or even when the buildings are still in the design phases (Ma et al. 2011). For some commercial buildings, DR strategies need to be programmed into the control system when the buildings are built; thus, it is important to compare different load shifting strategies before any tests are conducted.

Although traditional simulation tools, such as EnergyPlus, DOE2, eQUEST, and so on, are accurate enough for simulating the energy performance of a building and predicting the peak load reduction, the modeling process is complex, and the models are building specific (Pan et al. 2004). The difficulties of building detailed simulation models require the development of some quick simulation methods. One idea is to use EnergyPlus as the kernel but simplifying the modeling and the input processes.

This article describes the development of such method and verification of the method using data collected from a DR-tested building. Simulation software called Demand Response Estimator (DRE) has been developed with the simplified simulation method. This article first explains the principles behind the simplifications through a thermal energy balance analysis of an air-conditioned building. Then the building model used in the software and some important features are introduced. Finally, a case study using the experiment results of an office building in California is presented.

Description of the simplified simulation method

Principles for simplification

The relationship between the zone air temperature and the disturbance (outside temperature, solar radiation, indoor heat source, air conditioning, and so on) can be expressed in the following thermal balance equation. For air-conditioned buildings, the balanced equation for indoor air is shown in Equation 1, which is used in zone and air system integrations in EnergyPlus:

$$\rho_a v_a c_a \frac{\partial T_{in}(t)}{\partial t} = \sum_{i=1}^{n_{surfaces}} Q_{surface}(t) + \sum_{i=1}^{n_{sources}} Q_{in}(t) + Q_{inf}(t) + Q_{ac}(t), \tag{1}$$

where the term on the left-hand side is the energy stored in zone air; ρ_a, v_a, and c_a denote the density, volume, and specific heat of the indoor air, respectively; $Q_{surface}$ stands for the convective heat transfer from the zone surfaces (subscripts e, p, and f denote the interior surfaces of envelops, surfaces of interior partitions, and surfaces of furniture, respectively); Q_{in} is the sum of the convective heat gains from the interior heat source; Q_{inf} denotes the heat transfer due to infiltration of outside air; and Q_{ac} stands for the output of the air-conditioning system.

In the DR estimate, only the load change and the zone air temperature variation in a short time period, typically 1 to 3 h, is utilized. The cooling load removed by the air-conditioning system normally has a fixed relationship with the energy consumption of the system, which can be expressed as Equations 2 and 3 (Standardization Administration of the People's Republic of China 2007). The following simplifications were made based on this principle:

$$Q_{ac} = EER_S \cdot \sum N_i, \tag{2}$$

$$EER_S = \frac{1}{\frac{1}{EER_r} + \frac{1}{WTF_{chw}} + \frac{1}{EER_t}}, \tag{3}$$

where EER_S denotes the energy efficiency ratio of the whole air-conditioning system; N_i is the power consumption of the air-conditioning system, which includes the chiller, cooling water pump, cooling tower, terminal, and so on; EER_r is the energy efficiency ratio of the refrigeration parts; WTF_{chw} is the efficiency ratio of the transport system; and EER_t is the energy efficiency ratio of the terminal.

Simplification of the envelop

For one surface, $Q_{e,surface}$ can be expressed as

$$Q_{e,surface} = h_e \left(T_{e,surface} - T_{in}\right) A_{e,surface}, \tag{4}$$

where h_e is the surface convective coefficient and can be set as an empirical value or calculated through some empirical equations (Yazdanian and Klems1994; Loveday and Taki 1996; ASHRAE 2005), $T_{e,surface}$ stands for the surface temperature, and $A_{e,surface}$ denotes the area of the surface.

For any exterior surface (except for the window), $T_{e,surface}$, that is, $T_{e,i}$, follows the transient one-dimensional heat conduction equation:

$$\frac{\partial T_e}{\partial t} = a_e \frac{\partial^2 T_e}{\partial x_e^2}. \tag{5}$$

The boundary conditions for Equation 3 are expressed as

$$-\lambda_{e,o}\left(\frac{\partial T_e}{\partial x_e}\right)_{x_e=0} = h_{e,o}\left(T_{out} - T_{e,o}(t)\right), \tag{6}$$

$$\lambda_{e,i}\left(\frac{\partial T_e}{\partial x_e}\right)_{x_e=\sigma_e,} = h_{e,i}\left(T_{in} - T_{e,i}(t)\right), \tag{7}$$

where $\lambda_{e,o}$ and $\lambda_{e,i}$ denote the thermal conductivities of the outside and the inside materials of the exterior envelop, which can be considered as constants for certain materials; $h_{e,o}$ is the convective coefficient of the outside surface, which can be determined as $h_{e,i}$; and T_{out} stands for the equivalent ambient temperature, for example, when solar irradiation is considered, T_{out} equals the sol-air temperature (Yam, Li and Zhang 2003).

Combining Equations (1) and (5), $T_{e,surface}$ of the exterior envelop, i.e., $T_{e,i}$, can be obtained using numerous methods (Jan et al. 2011), e.g., finite-difference calculation.

Using Equations (2) to (5) and under the same outside weather condition, heat exchange between the interior surfaces of the exterior envelop and indoor air only depends on the envelop materials of the building and envelop surface areas of each side. This implies that the shape of each side is not an issue and has no effects on $Q_{e,surface}$. Thus, in the simulation, different building shapes can be transformed into a simple cube model that has the same side areas as the side areas of the original building, and the direction of the building can be defined as the degree of the north axis in DRE.

In the simplified simulation software, the envelop materials are represented by an integrated value for a certain building type (e.g., an office building) of a given region (e.g., a certain weather zone in California), which is obtained from a regional standard, meaning that only the length, width, and height need to be defined to describe an exterior envelop in DRE.

The heat transfer through a window is much more complicated. However, after the area of the window on each side and the type of window are defined, the heat transfer process can be simulated in EnergyPlus. Thus in DRE, the description of a window is simplified into the "window-to-wall ratio" of each side. The window area is fixed after the length, width, and height are defined, and the window thermal properties are defined in the local building codes.

Simplification of the interior partitions and furniture

Both the interior partitions and the furniture for a typical model used in DRE have already been set according to the local standard or survey. Thus, other than the number of stories, no description is needed for the interior partitions and the furniture.

Simplification of the interior heat source

Interior heat sources, $\sum_{i=1}^{n_{sources}} Q_{in}(t)$, e.g., people, are simplified as two parameters: Peak occupancy and occupancy schedule, which are the percentages of peak occupancy at each hour. The schedule is the same as that defined in the simulation of the local code compliance. Only the peak occupancy, lighting power, equipment power, and schedules describing the interior heat source are required to be inputted.

Simplification of the air-conditioning system output

In DRE, the office building model has two types of HVAC systems: a water-cooled chiller with variable air volume (VAV) systems and direct expansion air-conditioning with cooling by VAV systems. Both of these HVAC systems are auto-sized, and users do not need to build the air-conditioning system themselves; rather, one of them is chosen to simulate the system of the real building. The heat transfer due to infiltration of outside air, that is, $Q_{inf}(t)$, is also a default value for a certain building model.

Typical office model

A DR simulation is different from a traditional simulation, which only focuses on the reduction of the peak electricity

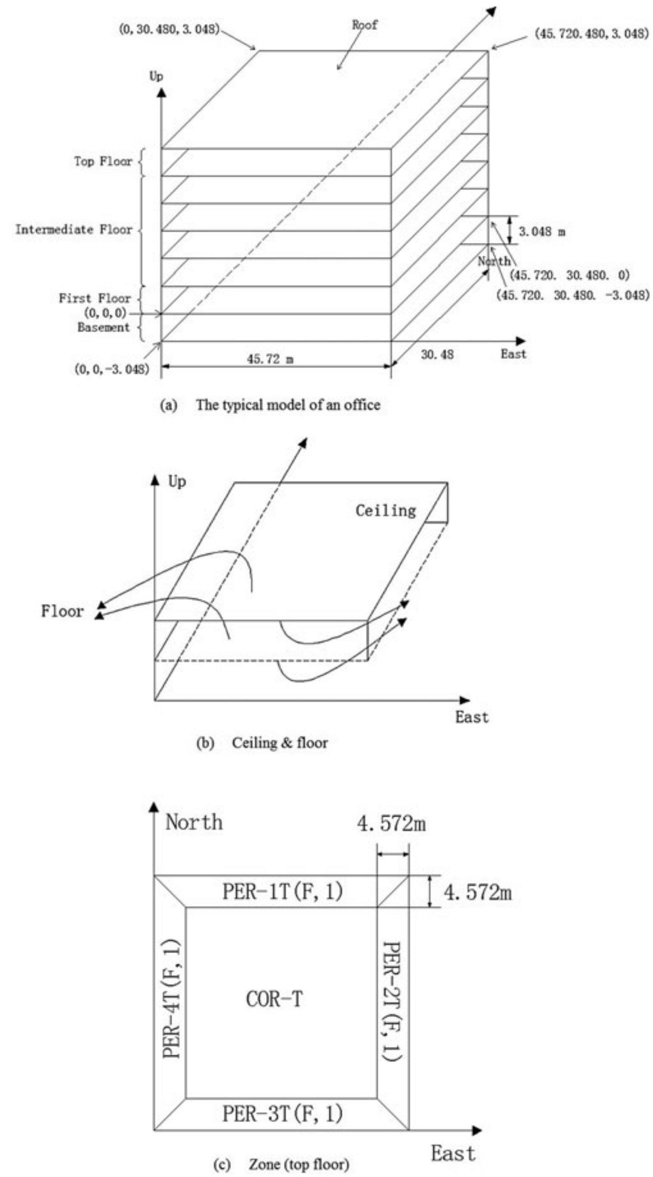


Fig. 1. Typical office building model. a. Typical model of an office. b. Ceiling and floor. c. Zone (top floor).

consumption and determines whether the zone temperature is in a comfortable range. Thus, some elements that have little influence on the DR estimate can be ignored or simplified. Currently, DRE has only one typical office building (Huang et al. 1991), which is used to simplify the modeling process, as shown in Figure 1.

For inputs of the building geometry in DRE, users can define the number of stories, length, width, and height of the floor according to the actual building. The construction of the building model in DRE depends on the climate zone. Because most buildings are built in accordance to the building code minimum requirements, DRE uses these minimum requirements as the descriptions of the building construction materials. The software has a default value for each climate zone, as described in California Title 24 Standards. The offices

Table 1. Required inputs of DRE.

Type	Input parameter
Building	Building type (only office at present), stories, length, width, height, mass level (high, medium, low), direction (north axis)
Internal heat source	Peak occupancy, lighting power, equipment power
Window	Window-to-wall ratio (west, east, south, north)
HVAC system	System type (water cooled/air cooled), sizing factor
Operation schedules	HVAC schedule, air loop set-point schedule, water loop set-point schedule, people, lighting, equipment schedule
DR strategies	Same as operation schedules

are modeled with steel frame constructions with lightweight windows. Each floor is divided into five zones: four perimeter zones and one core zone. The depth of the perimeter zone is 15 feet.

Summary of the simplifications (the minimum required inputs)

According to the simplifications mentioned above, engineers do not have to construct detailed building simulations for estimating the DR peak load reduction. Thus, only a limited number of parameters is needed to describe the model. The minimum required inputs for office buildings are shown in Table 1. Apart from the parameters shown in Table 1, users should also choose a climate zone and set a utility tariff for cost calculations, which is not an emphasis of this article.

Software features

DRE is an open-source software that can be freely download and has been used in California by one of its utility companies. DRE consists of three main parts: inputs, output, and internal data process. The DRE basic structure, data transmission, and relationship between each part are shown in Figure 2, where some necessary inputs mentioned before are needed. Some of the DRE interfaces are shown in Figure 3. Figure 3a is the “Building Site” page, where users can define the parameters of the building, windows, and HVAC system. Figure 3b is the “DR Strategies” page, where the DR control strategy and schedule are defined and which has the same format as the “Operation Schedules” page (used for the description of DR strategy and schedule).

Case study

The accuracy of the simplifications and the accuracy of the DRE software were verified through experiments and simulations of one office building in California. The building researched in this study is a medium-sized government office located in Santa Rosa, CA.

Basic information

The building is approximately 80,000 ft^2. It has three layers with a moderate structure, six concrete floors, and four concrete external walls. Office areas have medium furniture densities with standard commercial carpeting on the floor. The window to wall ratio is 0.67. The north and the south façades are glazed, and the glazed percentage is significantly smaller in the east and west façades. The internal equipment load and lighting load are typical loads for an office building. The total number of occupants is approximately 100 in the office areas.

The HVAC system pre-heats or pre-cools the building from 5:00 a.m. until 8:00 a.m. The working time is from 8:00 a.m. to 5:00 p.m. The whole mechanical system has no major faults, except for a small-capacity fan coil and some balance problems in the air-line system. Due to the lack of a reheat coil, there are some small problems in the temperature control. There are a few comfort complaints in the building, averaging two to three complaints per month, regarding the building being too warm or too cold.

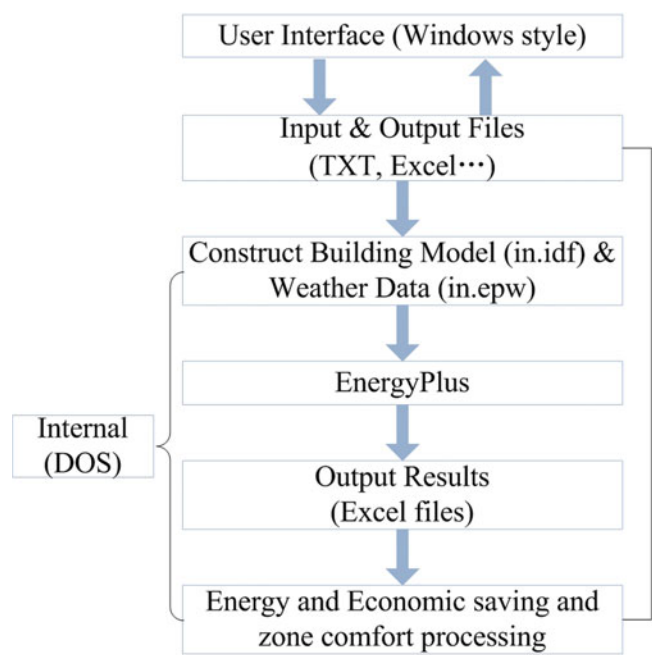
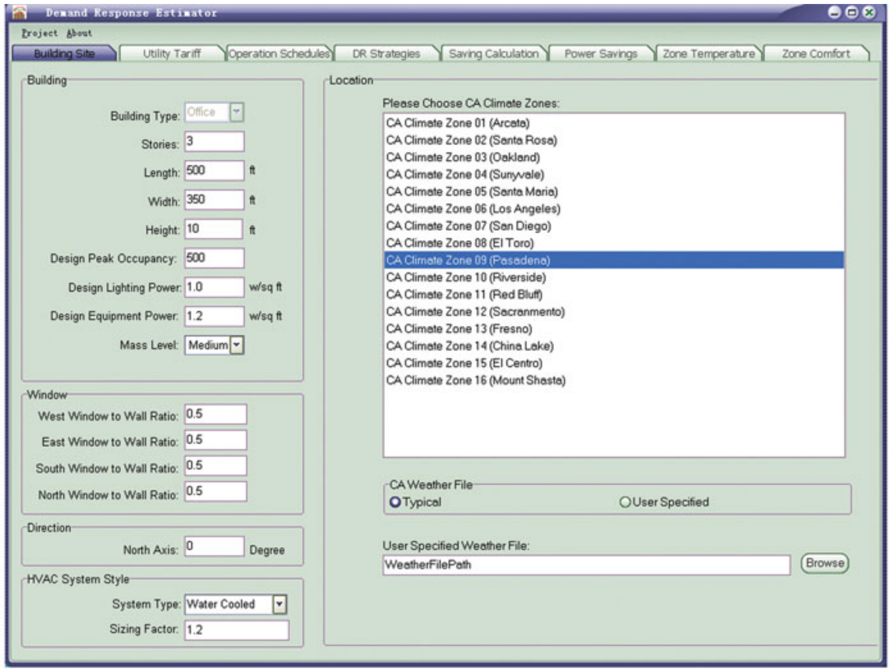
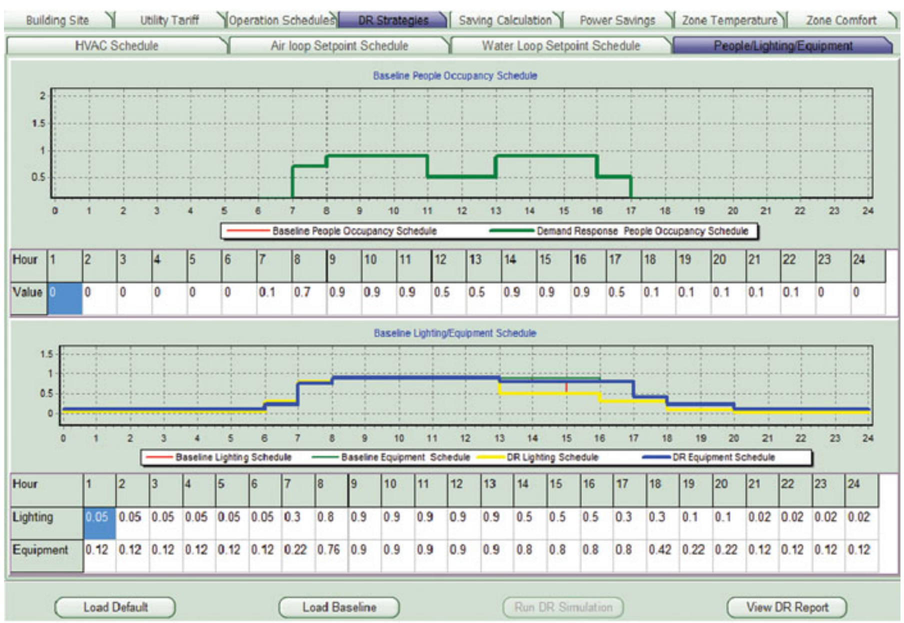


Fig. 2. Structure of DRE. a. “Building Site” page of DRE. b. “DR Strategies” page of DRE.



(a) "Building Site" page of DRE



(b) "DR Strategies" page of DRE

Fig. 3. Some interfaces of DRE.

Control strategies

Two pre-cooling and temperature reset strategies are shown in Figure 4. Usually, the building operates at a constant 72°F set-point through the start and occupied periods. The indoor temperature increases after the system switches off at 5:00 p.m. Under normal operation, the temperature for each zone varies between 70°F and 75°F with an average temperature of 72°F.

Strategy 1 is "pre-cooling + zonal reset." In this strategy, the set-point is 70°F for every zone from 5:00 a.m. to 2:00 p.m. Then the set-point rises to 78°F from 2:00 p.m. to 5:00 p.m., and the system is shut off after 5:00 p.m. for regular operation.

Strategy 2 is "extended pre-cooling + zonal reset." Here, the system starts at midnight, and from 12:00 a.m. to 5:00 a.m., the set-point is 68°F to pre-cool the concrete structure significantly. From 5:00 a.m. to 2:00 p.m., the set-point

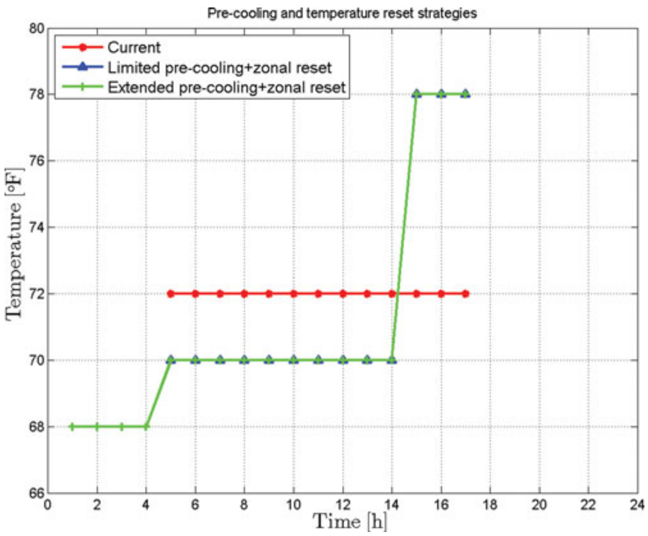


Fig. 4. Pre-cooling and temperature reset strategies.

rises to 70°F, and after 2:00 p.m., the set-point rises to 78°F. The difference between these two strategies is the extension of the pre-cooling period. The effect of the extension on peak load shifting can be estimated through experiments and simulations.

The baseline day is defined according to the outside air peak temperature. Under regular operation, utility and weather data for a certain period were analyzed to determine the relationship between the daily outside air peak temperature and the daily peak demand. There is a strong correlation between the peak power demand and the outside air peak temperature, which is shown in Figure 5. Thus, the baseline day was chosen for every test day according to the similarity of the outside air peak temperature.

All of the test days are divided into two groups according to the outside air peak temperature. They are defined as warm days, when the outside air peak temperature is between 78°F and 84°F, and hot days, when the outside air peak temperature is between 84°F and 90°F. Both the temperature and the temperature variation are similar for test days and baseline days. Eight tests were conducted: five pre-cooling + zonal reset tests and one extended pre-cooling + zonal reset test were conducted on warm days, and two extended pre-cooling + zonal reset tests were conducted on hot days.

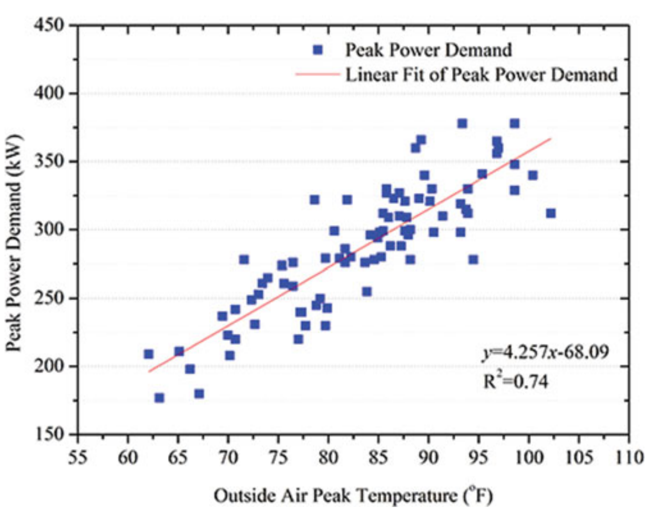


Fig. 5. Relationship between peak power demand and outside air peak temperature.

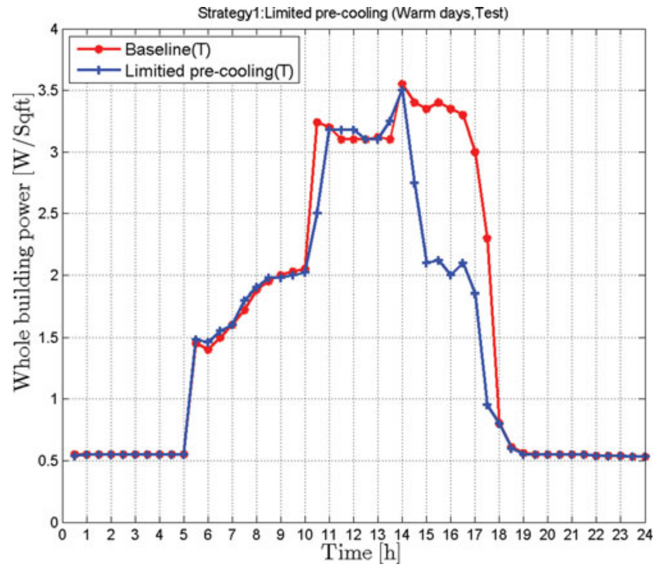


Fig. 6. Limited pre-cooling test results on warm days.

Results

Both experimental data and simulation data show significant shifts in the peak load for the two pre-cooling strategies. The test and simulation results are shown in Figures 6–11.

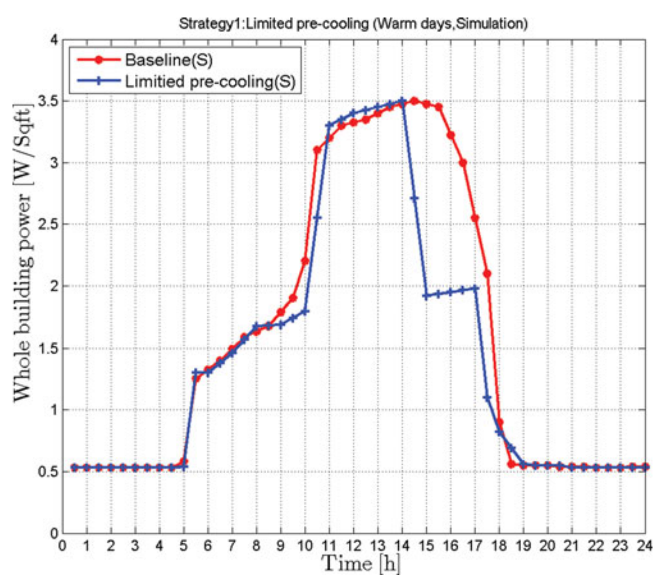


Fig. 7. Limited pre-cooling simulation results on warm days.

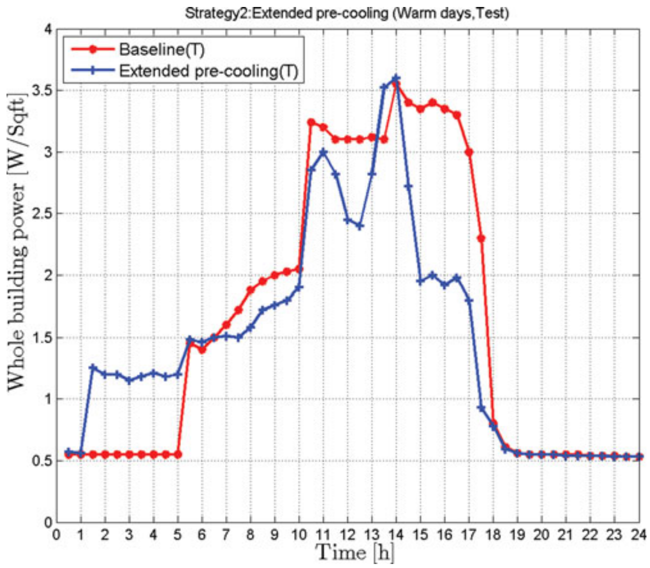


Fig. 8. Extended pre-cooling test results on warm days.

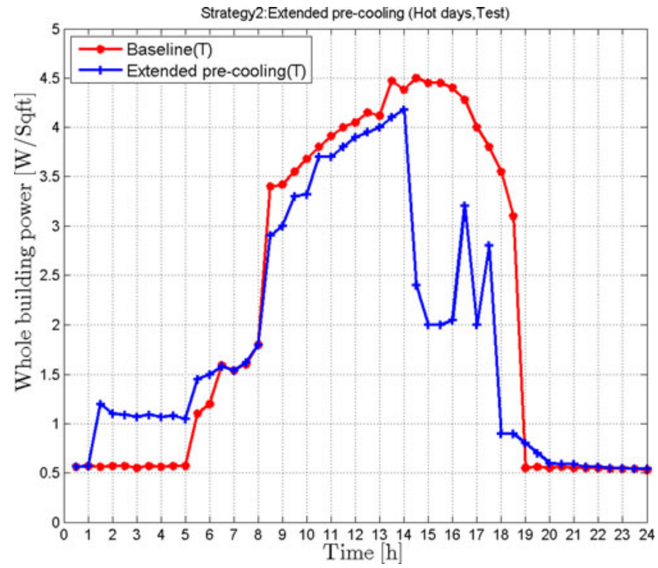


Fig. 10. Extended pre-cooling test results on hot days.

Figure 6 shows the test (T) result of control strategy 1, that is, pre-cooling + zonal reset, on warm days. The increase of the zone temperature set-point causes the cooling demand to become zero; hence, cooling shuts off automatically after 2:00 p.m., and the demand of the whole building is decreased by 1.14 W/ft^2 on average.

Figure 7 shows the simulation (S) result of control strategy 1 on warm days. According to the basic information of the building, occupant information, equipment information, and building schedule, DRE "Building Site" is set. The baseline control strategy is set in "Operation Schedule." Then, the control strategy is adjusted and the zone air set-point is reset, according to strategy 1—pre-cooling + zonal reset—in the "air loop set-point" of the DR strategy. Other sets are the same as the baseline. The simulation result of a particular day, in which the weather (outside peak air temperature and temperature change trend) is similar to the test day, is chosen as the simulation result for warm days. The weather data can be found in the weather files. The demand reduction of the whole building in the simulation is 1.12 W/ft^2 on average after resetting the temperature, which is in close agreement to the test result.

Figure 8 shows the result of strategy 2 for warm days. In the test of extended pre-cooling, when cooling starts up at midnight, the energy consumption is increased compared to the baseline, and in the morning, the energy consumption is slightly decreased compared to that of strategy 1. After 2:00 p.m., the demand decrease of the whole building is also

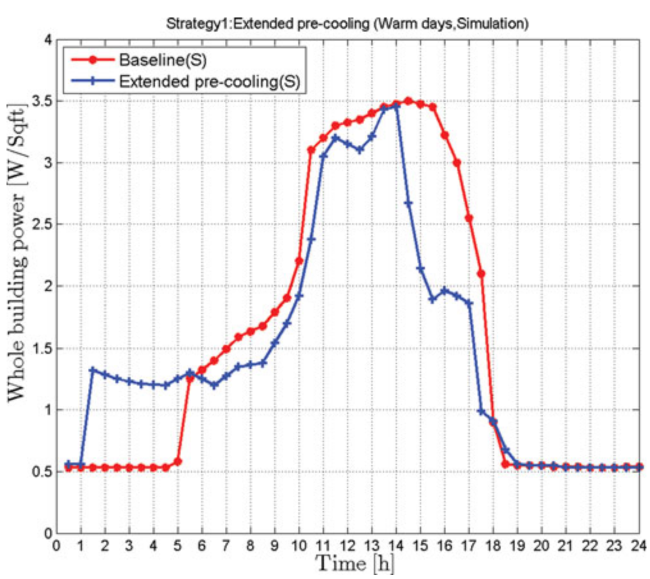


Fig. 9. Extended pre-cooling simulation results on warm days.

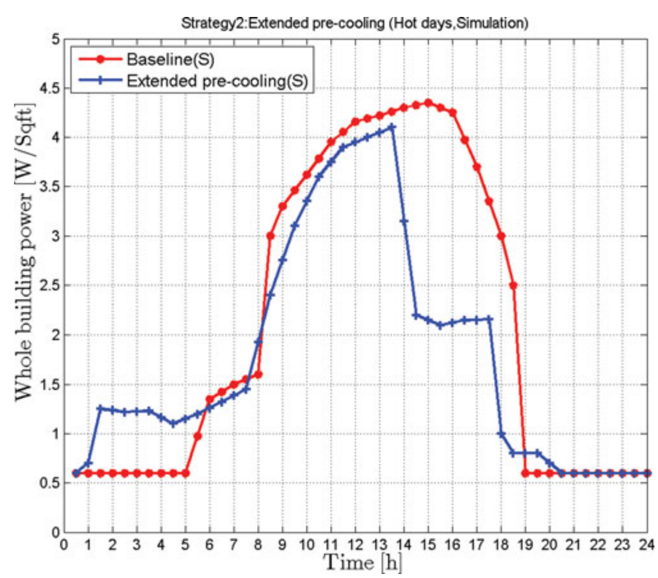


Fig. 11. Extended pre-cooling simulation results on hot days.

Table 2. Results of tests and simulations.

		Peak load decrease (from 2:00 p.m. to 5: p.m.)						
		Test			Simulation			
Strategy	Day type	Baseline	DR	Decrease	Baseline	DR	Decrease	Relative error (%)
1	Warm days	3.40	2.75	0.65	3.50	2.71	0.79	
		3.35	2.10	1.25	3.47	1.92	1.55	
		3.40	2.12	1.28	3.45	1.93	1.52	
		3.35	2.00	1.35	3.22	1.95	1.27	
		3.30	2.10	1.20	3.00	1.96	1.04	
		3.00	1.85	1.15	2.55	1.98	0.57	
		Average		1.15	Average		1.12	2.03
2	Warm days	3.40	2.72	0.68	3.50	2.67	0.83	
		3.35	1.95	1.40	3.48	2.14	1.34	
		3.40	2.00	1.40	3.45	1.89	1.56	
		3.35	1.92	1.43	3.23	1.96	1.27	
		3.30	1.98	1.32	3.00	1.92	1.08	
		3.00	1.80	1.20	2.55	1.85	0.70	
		Average		1.24	Average		1.13	8.88
	Hot days	4.50	2.40	2.10	4.33	2.20	2.13	
		4.45	2.00	2.45	4.35	2.15	2.20	
		4.45	2.00	2.45	4.30	2.10	2.20	
		4.40	2.05	2.35	4.25	2.13	2.13	
		4.28	3.20	1.08	3.98	2.15	1.83	
		4.00	2.00	2	3.70	2.16	1.55	
		Average		2.27	Average		2.00	11.75

approximately 1.24 W/ft^2 on average. The difference between the effects of strategy 1 and strategy 2 is not significant, which could possibly be due to differences in the weather or occupancy.

Figure 9 gives the simulation result of strategy 2 on warm days. Based on the simulation result of strategy 1, that is, pre-cooling+ zonal reset, and according to strategy 2, that is, extended pre-cooling + zonal reset, the air loop set-point schedule in the DR strategy is adjusted to simulate strategy 2 on warm days. The baseline strategy is the same as before. The simulation results show that the demand decrease of the whole building is 1.05 W/ft^2 on average during the DR period.

The test result of strategy 2 on hot days is shown in Figure 10. When compared to the baseline, electricity consumption is slightly lower in the morning, and the demand reduction is 2.27 W/ft^2 on average apart from the fault point during the afternoon peak time. During the experiment of strategy 2, the global temperature reset control strategy is not conducted properly; that is, the set-points do not reach 78°F in some of the zones, which leads to cooling being switched on at a time before 5:00 a.m. When the temperature reaches the unadjusted temperature, cooling starts again. After this problem is fixed, cooling is switched off until 5:00 p.m. as in the other tests.

The results of strategy 2 on warm days can be used and the result for a hot day extracted, in which the weather is similar to the test day, as the simulation result for hot days, as shown in Figure 11. In the baseline simulation, the temperature reset problem did not happen. On DR days, the demand reduction is 2.0 W/ft^2 on average after the temperature was reset.

The results of experiments and simulations are compared in Table 2, where the peak load decreases obtained from simulations and tests are fairly close to each other for the different strategies used on both warm days and hot days. The relative errors between simulations and tests for the predictions of average peak load decreases are 2.03% for strategy 1 on warm days, 8.88% for strategy 1 on hot days, and 11.75% for strategy 2 on hot days. All of them are acceptable for the prediction process.

In the case study, the errors for the hot days are greater than those of warm days. However, this result should not be taken as a general trend because the parameters that influence the load cannot be guaranteed to be the same between the DR day and its baseline day during the field test, which are set as the same values during the simulations. Hence, differences in these parameters would vary the error fluctuation;

$$Relative\ Error = \frac{Decrease_{average,test} - Decrease_{average,simulaiton}}{Decrease_{average,test}} \times 100\%. \quad (8)$$

In both simulation and experimental tests, the indoor temperatures were within the range of comfort. In the simulation, the temperature variation would not cause a thermal discomfort, as proved through the analogous test. Throughout the test, the indoor temperature never exceeds 75°F even in the "worst-case zone," and no complaint is received during the

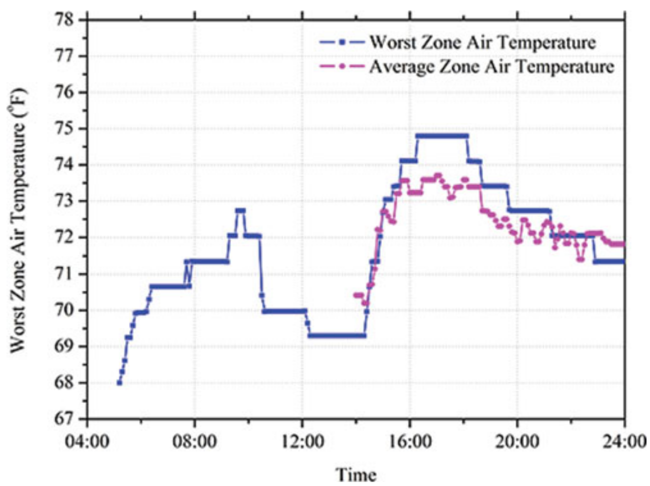


Fig. 12. Monitoring of zone air temperatures for the pre-cooling tests.

test. Figure 12 shows the zone temperatures for the worst zone during warm day tests for the pre-cooling strategies and the average zone air temperature measured by the control system. Even the temperature of the worst-case zone never exceeds 75°F.

Conclusions and further work

This article introduced an effective simplified calculation method to estimate DR peak load reductions, which uses EnergyPlus as a kernel but simplifies the modeling process. Based on this principle, an open-source software, DRE, is built to predict the DR peak load reductions of commercial buildings. The aim of the new method and tool is to estimate the potentials of a peak load reduction within a reasonable range when limited information of a building is provided.

In this research, the process of simplification is explained by a thermal balance analysis. Under the same weather conditions, the heat gain from building an envelope is only dependent on the materials and the surface area of each side. Thus, a typical cubic model with the same surface area can reasonably represent a building. This saves a large amount of efforts of constructing building simulation models for DR. In the simplified simulation tool, the material types are determined from local standards, and the interior heat source is described as schedules in the code compliance calculation. Typical air-conditioning systems have already been built inside the tool, and control strategies can be set easily.

To verify whether these simplifications are reasonable, two DR control strategies are implemented in an office building in California under two different weather conditions. All three peak load reductions obtained from simulations matched well with the test results, and the relative errors are 2.03% for strategy 1 on warm days, 8.88% for strategy 2 on hot days, and 11.75% for strategy 2 on hot days.

It can be concluded that the method and the software built on simplification principles are reasonably accurate in predicting the DR peak load reductions of office buildings. However, this tool is only able to simulate one building type, that is, an office building. More commercial building types, as well as HVAC systems, will need to be added to the tool in the future to facilitate the rapid expansion of DR control in the building sector.

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