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Simulation of energy performance of underfloor air distribution (UFAD) systems

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Simulation of Energy Performance of Underfloor Air Distribution (UFAD) Systems

BERG AWARDEE

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Abstract

This project was a simulation study of the energy performance of a prototype three-story office building configured for both conventional overhead (OH) air conditioning and underfloor air distribution (UFAD). Both the annual energy consumption and the peak demand were calculated using EnergyPlus v3.0 for the building in three California climate zones, Los Angeles, Sacramento and San Francisco. The sensitivity of the energy performance to the building configuration (e.g., window to wall area ratio, etc.) and other features of the building was studied. The main result of the study was that UFAD provides energy savings compared to OH in all three climate zones, both in terms of annual energy consumption and also in the reduction of peak demand HVAC annual energy reductions were greater in San Francisco but only marginally better than in the warmer climate zones of Los Angeles and Sacramento. A second major outcome of this study was improvements to the UFAD implementation in the recently released EnergyPlus v3.1. These involved improvements in stratification modeling in interior zones, addition of perimeter zone stratification models, creation of a whole building template model, and user documentation to facilitate use of the new capabilities. Finally, the effectiveness of various demand response actions such as raising the room setpoint temperature and reducing internal lighting and equipment loads was evaluated. Raising the setpoint temperature was found to be the most effective measure to reduce peak demand.

Key words

Underfloor air distribution, air conditioning, energy, peak demand, demand response, climate zones

Executive Summary

Introduction

Underfloor air distribution has the potential to provide a comfortable interior air-conditioned space with less energy consumption than a traditional overhead system. This is because underfloor air distribution provides air at a higher supply temperature, which has more potential to use an air-side economizer, and through a low pressure plenum with consequent potential reductions in fan energy. It also has potential for improved demand response performance in reducing peak energy demand because of the associated thermal stratification.

The possibility of modeling underfloor air distribution energy performance has recently become available through the implementation of an underfloor air distribution module in the building energy simulation program EnergyPlus. The present study examines, through the use of EnergyPlus, the differences in energy usage and peak demand between overhead and underfloor for a generic three-story office building in three different California climate zones. Attention is paid both to average consumption and to the response to various demand reduction strategies such as reducing interior loads and increasing room set point temperatures.

Project Objectives

The goal of this project is to assess the potential for underfloor air distribution to reduce energy costs of cooling and heating buildings in California. It is also addressing strategies for the reduction in peak demand – demand response. Overall objectives are:

1. Determine energy savings of underfloor air distribution systems relative to conventional overhead systems.
2. Assess the potential demand reduction savings of underfloor air distribution systems

Detailed objectives are listed in the body of this report.

Project Outcomes

Energy performance of underfloor air distribution relative to conventional systems

A comparison of underfloor air distribution energy performance to two state-of-practice overhead systems for three California climates shows the following outcomes:

- Energy consumption of underfloor air distribution systems is sensitive to climate but not to other building design variables of window to wall ratio and internal load.
- Within all climates, optimum energy performance for underfloor air distribution systems occurs at air handler unit supply temperatures equivalent to those of overhead systems, 13.9°C (57°F). At this optimum temperature, underfloor air distribution energy savings ranged from 7.7-33.3 percent for SF, 2.1-29.3 percent for Los Angeles, and 8.3-28.3 percent for Sacramento.
- Different underfloor air distribution system supply distribution ductwork amounts resulted in fan energy increases of 60 percent over a supply fan static pressure range of 0.5 to 1.125 kPa

(2 to 4.5 iwc), representative of design with no supply distribution ductwork to a fully ducted system.

- For diffuser products typical of today's practice, the benefits of stratification are not
- increased by adding more diffusers. However, simulations with idealized stratification indicate that measures to increase stratification hold promise of improving performance by 7.1 percent.

Underfloor air distribution Demand Performance assessment

A comparison between overhead and underfloor air distribution for various demand response actions shows the effectiveness of DR in underfloor air distribution in three Californian climate zones:

- Increasing the room setpoint temperature provides higher energy savings and peak demand reduction than reducing equipment or lighting loads.
- There is a small (5 percent) advantage in reducing lighting rather than equipment consumption for both the average energy and the peak energy reduction.
- There are slight improvements in terms of the normalized average energy and peak energy consumption by delaying the start of the demand response period. The main benefit (4 percent) is due to increasing room setpoint temperature, but the impact of reducing equipment or lighting loads was minimal.
- Simulation results for various weather categories imply that demand response activities that reduce convective heat transfer of internal load are not influenced by weather conditions
- Underfloor air distribution produces reductions in average energy and peak demand over a DR period compared to overhead by in the range of 6~10 percent when the setpoint temperature is higher than 26°C (78.8°F).
- Increasing room setpoint temperature is most effective as a demand response action on 'hot' (greater than 29.4°C (85°F) days.

Conclusions

Energy performance

Contrary to expectations of researchers, underfloor air distribution overall ventilation performance (based on site energy usage) was best when operated with air handler supply temperatures equal to that of overhead systems 13.9°C (57°F) for all climates studied. For a supply temperature of 57°F , underfloor air distribution outperformed overhead in three climates by 7.7-33.3 percent (San Francisco), 2.1-29.3 percent (Los Angeles), and 8.3-28.1 percent (Sacramento) when compared to "good" practice and "standard" practice overhead systems, respectively.

Differences in the amount of supply distribution ductwork (from no ductwork to fully ducted) can have a significant impact on fan energy consumption. However, the thermal performance impact of supply ductwork configurations (series, parallel, ducted) has very little impact on underfloor air distribution ventilation energy consumption.

Improved underfloor air distribution energy performance with increased stratification is not easily realized using state of practice diffusers, but a savings of 7.1 percent was shown for idealized stratification indicating some potential for improving the performance of these systems in the future.

Demand performance

The effectiveness of demand response actions on baseline-building configurations of overhead and underfloor air distribution, with a specified internal load configuration (Internal Load #1) for three different climate zones was examined. Increasing the room setpoint temperature shows higher energy savings and peak demand reduction compared to reducing equipment and lighting loads, and underfloor air distribution is more effective compared to overhead in Los Angeles and Sacramento where higher electricity demands are needed during summer..In practice, the improved demand response effectiveness of underfloor air distribution provides improved occupant thermal comfort and achieves better electricity demand reduction than overhead.

Recommendations

The following list summarizes recommendations for optimization studies and improvements to EnergyPlus:

Optimization studies

- Chiller leaving water temperature reset
- Air handler unit supply temperature reset
- Air handler unit return air bypass
- Core zone heating and minimum volume issues
- Plenum leakage and slab and raised floor insulation

EnergyPlus changes and improvements

- Sizing improvements
- Enhanced Perimeter zone model
- Window blinds control

Public Benefits to California

The work in this project will have a direct impact on proposed inclusion of EnergyPlus as a simulation tool for energy compliance under Title 24. The results provide data that will inform current codes used for Title 24 compliance and building industry practitioners who design and operate UFAD systems.

The results show that annual energy savings of underfloor air distribution compared to overhead are positive and depend on the climate zone (and assumptions for overhead systems used as a reference for comparison). The calculations also show reductions in peak demand compared to conventional systems particularly away from the temperate coastal zone.

Introduction

Underfloor air distribution has the potential to provide a comfortable interior air-conditioned space with less energy consumption than a traditional overhead system. This is because underfloor air distribution provides air at a higher supply temperature, which has more potential to use an air-side economizer, and through a low pressure plenum with consequent potential reductions in fan energy. It also has potential for improved demand response performance in reducing peak energy demand because of the associated thermal stratification.

The possibility of modeling underfloor air distribution energy performance has recently become available through the implementation of an underfloor air distribution module in the building energy simulation program EnergyPlus. The present study examines, through the use of EnergyPlus, the differences in energy usage and peak demand between overhead and underfloor for a generic three-story office building in three different California climate zones. Attention is paid both to average consumption and to the response to various demand reduction strategies such as reducing interior loads and increasing room set point temperatures.

This project falls in the Building Energy area of PIER and the specific objectives discussed below can be categorized under two main themes first, to determine energy savings of UFAD systems relative to conventional overhead systems and, second, to assess the potential demand reduction savings of UFAD systems. The researchers compare the two systems for different California climate zones and also examine different demand response strategies such as raising the room setpoint temperature and reducing lighting levels and equipment loads.

Project Objectives

The goal of this project is to assess the potential for UFAD to reduce energy costs of cooling and heating buildings in California. It is also addressing strategies for the reduction in peak demand – demand response (DR). The specific objectives are:

1. Interface DOE prototype large commercial office building with Design-Builder.
2. Modify IDF file to include UFAD features and by developing “user interface” assistance tools.
3. Specify matrix to cover range of desired scenarios, for UFAD and OH comparison and DR response of UFAD.
4. Confirm that EnergyPlus has the capability perform the required calculations.
5. Demonstrate that the procedures to obtain needed data are clearly outlined.
6. Define metrics for stratification and comfort temperatures.
7. Define metrics for energy reduction and DR response.
8. Confirm that data have been collected in accordance with the simulation plan.
9. Compare the energy usage between UFAD and OH systems for the variables under consideration.
10. Check that desired stratification and comfort conditions are achieved, and determine any ranges of non-compliance.
11. Demonstrate the effectiveness of different DR strategies.
12. Implement modifications to the UFAD model within EnergyPlus to account for deficiencies revealed in the results.
13. Implement and test modifications in the capabilities of EnergyPlus to model practical situation.

14. Determine the potential benefits in different climatic zones and for different DR strategies.
15. Determine the best venues to disseminate the results of this study and any tools developed to the industry.

Project Approach

This section describes the approach, method and materials used for each task.

Establish EnergyPlus model

EnergyPlus is a building energy simulation program developed and supported by the U.S. Department of Energy. Based on two predecessor programs DOE-2 and BLAST, but with greater capabilities than either, it exceeds the capabilities of many other building simulation programs. The following key features make EnergyPlus the best choice for this project.

- *Thermal decay* – In UFAD systems, thermal decay, the temperature rise of the conditioned air due to convective heat gain as it travels through the underfloor supply plenum, is an important phenomenon that is essential to accurate simulation of UFAD performance. EnergyPlus has the capability to model each underfloor plenum as a separate zone, and calculate the heat, mass, and energy balances to simulate this thermal decay.
- *Simultaneous simulation of zone, system and plant* – in contrast to other tools EnergyPlus performs the system and plant simulation, and the air and surface heat balances simultaneously. This is essential for realistic energy modeling.
- *Radiant heat transfer* – EnergyPlus conducts an energy balance on each surface including the radiant heat exchange between surfaces and internal loads, essential for systems with non-uniform environments such as UFAD.

Model characteristics

Building geometry. The CBE (Center for the Built Environment) Prototype is a three-story rectangular office building with an aspect ratio of 1.5. Each 5,576 m^2 (60,000 ft^2) floor plate consists of four perimeter zones, an interior zone and a service core[1], representing approximately 40, 45 and 15 percent of the floor area, respectively. The baseline window-to-wall ratio (WWR) is 40 percent with window locations evenly distributed in the walls of each exposure; varying only the height of the window changes the window size. Key features of the building geometry and construction details are contained in Appendix A. Both an OH system and a UFAD system with a supply plenum zone below each occupied zone can be simulated with CBE Prototype. The total floor-to-floor height and the occupied zone floor-to-ceiling height are the same for OH and UFAD.

Internal Loads and Schedules. Three different internal load “scenarios,” (Table 10, Appendix A) were constructed to cover low to high internal load conditions. The total combined internal loads assumed 75W per person. These values resulted from preliminary studies (Appendix A). Two schedules were used, one for people and internal loads and one for HVAC start and stop. Schedules for people and internal loads are 0800 to 1800 weekdays, and 0800 to 1200 on weekends. HVAC operates from 0500 to 1900, to allow for morning warm up and shutdown.

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[1] The service core was not actively modeled in this project; no loads or schedules were applied. Occupancy, lighting, and equipment intensities need to be adjusted appropriately when comparing to other work where service cores are not included.

HVAC Systems and plant. HVAC air distribution system models for OH and UFAD were similar. The overhead model employs variable air volume (VAV) boxes with hot water reheat coils for all zones. Two baselines were created for the OH system to represent the range of common practice (see section on simulation procedures and Table 3). The UFAD system represents a fan coil unit (FCU) system, consisting of swirl diffusers in interior zones and linear bar grille diffusers in the perimeter zones served by a variable speed series FCU. The FCU shuts off when zone temperatures are in the heating-cooling dead band. An OH VAV reheat system serves the service core although no loads assigned to this zone.

Both systems were served by a single variable speed central station air handling unit (AHU) including a return air economizer, chilled water cooling coil, and hot water heating coil. A constant static pressure set point controls the AHU speed. The central plant consisted of a central centrifugal chiller with variable speed pumps and cooling tower. A gas fired hot water boiler provided heating to all heating coils. Complete details of the system and plant designs appear in Appendix A.

Develop simulation procedure

Three categories of energy simulations were conducted: (1) assessment of the impact of building design parameters on UFAD and OH energy performance; (2) energy use comparisons due to differences in system design and operating conditions between UFAD and the OH baselines; and (3) comparison of various UFAD design alternatives to the UFAD baseline.

Develop performance metrics

ASHRAE Standard 55 [ASHRAE 2004] specifies allowable vertical air temperature difference in rooms: 3°C (5.4°F) between head and ankles (1.7 m [67 in.] to 0.1 m [4 in.]). In all other ways, comfort levels for stratified systems are supposed to conform to Standard 55. However, in stratified rooms controlling and determining comfort conditions with a single temperature measured by a 4-ft (1.2-m) high thermostat is not valid. EnergyPlus does not produce a realistic temperature profile in the room; two well-mixed layers represent the room temperature distribution. This is accurate enough for energy analysis considerations [Liu and Linden 2006], but may not be for comfort analysis.

Simulations were conducted for the same building with two different HVAC systems. The energy performance was determined by comparing HVAC energy performance between UFAD and OH. Figure 2 shows the HVAC component energy use intensity (EUI) results. The primary metric used is site-based annual HVAC EUI (kBtu/ft^2/yr). Two baseline cases for OH bracket the expected range of variation in performance yielded by typical design practice. Complete results of HVAC component-level graphs similar to Figure 2 are included in Appendix G. To illustrate the impact of building level and source based consumption, Figures 1 and 2 in Appendix G were prepared for baseline cases.

Demand Response (DR) consists of a set of strategies or activities to reduce Peak Electricity Demand (PED). Activities such as dimming or shutting off interior lighting, reducing equipment loads or increasing room set-point temperature are methods to respond to a DR request. These DR activities operated manually or by semi- or fully-automated controls, are simple but effective means for reducing electric demand. [Kiliccote, Piette & Hansen 2006]

Careful design of DR activities and their scheduling is important because they can affect the comfort of building occupants. In this simulation study, simple but realistic, semi-automated DR activities, in which a specific building operation is followed by pre-programmed operating schedules were used.

To estimate the effectiveness of DR activities, this study uses two newly-defined parameters, Peak Elect. Demand Reduction (PEDR) and TAEDR (Time Averaged Elect. Demand Reduction).

Conduct simulations in accordance with the simulation plan

To maintain continuity and minimize errors and debugging a single whole building model was developed by CBE researchers. The researchers used the identical model to conduct DR simulations. Each team developed their own simulations plan and input/output interfaces and conducted simulations according to their respective plans.

Analyze the results

Hourly and annual data are obtained from EnergyPlus output reports to match the metrics used to analyze performance of UFAD vs OH. Various Excel and Matlab based analysis tools create tables and charts contained in this report based on this output data. In addition, debugging of the program was facilitated by an Excel input/output interface developed by the researchers that presented hourly results in a convenient manner.

Improve the UFAD capabilities in EnergyPlus

Many of the EnergyPlus functions necessary to conduct this study are relatively new and untried. Changes and modifications were anticipated and researchers planned on having a close working relationship with EnergyPlus developers to resolve issues as they came up. HVAC systems configurations and default input parameters are not optimized and were refined by the research team.

Evaluate the benefits to California ratepayers

The focus of this project is on determining the energy savings potential for UFAD systems, not on development of the technology itself. Therefore, outcomes from this project establish performance potential for a technology that has been (and is being) developed by others.

There is no standard or accepted approach for estimating benefits of a given technology. A variety of methods are used each of which is based on manifold assumptions that are difficult or impossible to verify. The methods used here are based on using the performance savings from simulation studies along with published end-use data for existing buildings. [Itron 2006] published by the California Energy Commission. Since UFAD systems are predominantly used in large offices and new construction, energy benefits are estimated for this market segment based on industry provided UFAD penetration estimates. Benefits are based on consumption savings for new construction for an assumed construction growth rate; demand response savings calculations are considered to be outside the scope of this project.

Evaluate the effectiveness of various paths to reach consumers

Since the primary "product" for this project is a UFAD simulation tool (i.e., EnergyPlus whole building model for EnergyPlus) the "consumers" for the products of this project are building practitioners such as engineers and architects who design and operate commercial buildings. The approach for evaluating various paths is to identify ways that these practitioners can be reached.

Project outcomes

Interface DOE prototype large commercial office building with Design-Builder

The researchers planned to use whole-building prototype models derived from previous work by the research team using Design Builder, a user interface for EnergyPlus. This procedure proved to be unworkable due to constraints imposed by the object naming structure and simulation conventions that Design Builder uses. The final model (the CBE Whole-building Prototype, or CBE Prototype) is based on a complete revamping of the input structure better suited to the needs of this project. A development version of EnergyPlus v2.1 released in October 2007 is used for all simulation work of this project. EnergyPlus v3.1, released in April 2009 contains all of the modifications made during this and previous projects by the research team.

Modify IDF file to include UFAD features and by developing user interface assistance tools

EnergyPlus uses plain text input files to describe the building geometry, systems, constructions, climate, etc., and plain text output files. Many hundreds of runs were made during the development, testing, and debugging of the EnergyPlus models during the course of this and previous projects [Bauman 2007]. The research team developed a Microsoft Excel-based user interface program to facilitate the simple execution and analysis of these runs. This program uses the Visual Basic for Applications (VBA) computer code in combination with standard Excel spreadsheet elements to create a simple and easy-to-modify simulation interface. The output processor used for DR analysis was a Matlab Graphical User Interface (MGUI). A description of both interfaces is included in Appendix C.

Specify matrix to cover range of desired scenarios for UFAD and OH comparison and DR response of UFAD

Table 1 summarizes all the runs and comparisons made between each UFAD parameter and its OH complement or between UFAD parameters. City selection was based on population and the known and expected prevalence of UFAD installations.

In addition, a special set of runs was made to explore the impact of variations from the baselines for UFAD and OH. For UFAD, these included variations from the series configuration of supply plenums between interior and perimeter zones, including parallel and ducted arrangements. Varying the number of diffusers and using an idealized fixed stratification level was used to investigate the impact of stratification. For OH, variations included supply duct heat gain, typical practice of using 30 percent minimum fractions for perimeter VAV boxes, and greater static pressure set points of 0.375 kPa (1.5 iwc).

Table 3 summarizes the baseline differences between UFAD and OH. OH has two baselines; Base Case 1 (OHBC 1) reflects “good” design practice, and Base Case 2 (OHBC 2) reflects common Title 24 prescriptive practice.

Table 1. Matrix of simulation runs

			Run comparisons	
Parameter	**Values**	**Purpose**	**UFAD Model**	**OH Model**
City	SF	Sensitivity to weather	x	x
	SC		X	X
	LA		x	x
WWR	20 percent	Sensitivity to perimeter vs. interior loads	x	x
	40 percent		X	X
	60 percent		x	x
Internal load level	#1	Sensitivity to internal load level	X	X
	#2		x	x
	#3		x	x
AHU SAT Setpoint	13.9°C (57°F)	Impact of AHU SAT	x	X
	15.6°C (60°F)		x	
	17.2°C (63°F)		X	
AHU Design Static pressure	0.50 kPa (2 iwc)	Degree of ducting in SA plenum	x	
	0.75 kPa (3 iwc)		X	
	1.125 kPa (4.5 iwc)		x	X
System Type	UFAD A (FCU system)	Impact of HVAC system type	X	
	UFAD B (VA system)		x	
	OH VAV single duct reheat			X
Stratification level	# 1	Impact of stratification in UFAD systems	x	
	# 2		X	
	# 3		x	

Large X indicates a baseline parameter

Table 2. Definitions for load and stratification levels shown in Table 1.

	Scenarios	**#1**	**#2**	**#3**
Room air stratification (RAS) specifications	Diffuser design ratio (DDR)	1.0	0.5	0.33
Internal load specifications	OH lighting, W/m^2 (W/ft^2)	10.8 (1.0)	11.8 (1.1)	12.9 (1.2)
	People sensible, W/m^2 (W/ft^2)	3.2 (0.3)	6.5 (0.6)	8.6 (0.8)
	Peak occupancy, m$^{2/}$person (ft^2/person)	22.3 (240)	11.2 (120)	8.4 (90)
	Sensible load, W/person	75	75	75
	Equipment W/m^2 (W/ft^2)	8.6 (0.8)	22.6 (2.1)	35.5 (3.3)
	WS load, W/Workstation	200	250	300
	Total, W/m^2 (W/ft^2)	22.6 (2.1)	40.9 (3.8)	58.1 (5.4)

Table 3. Summary of baseline configurations

Input parameter	OH Base case1	OH Base case 2	UFAD Baseline
AHU supply temp	13.9°C (57°F)	13.9°C (57°F)	17.2°C (63°F)
AHU Static press	1125 Pa (4.5 iwc)	4.5 (1125 Pa)	3.0 (750 Pa)
AHU part load shutoff	250 Pa (1.0 iwc)	375 Pa (1.5 iwc)	125 Pa (0.5 iwc)
Outside air rate	7.62 E-04 m^3/s/m^2 (0.15 cfm/ft^2)	7.62 E-04 m^3/s/m^2 (0.15 cfm/ft^2)	7.62 E-04 m^3/s/m^2 (0.15 cfm/ft^2)
System cycle at night	No	No	No
Zone Min airflow, percent max	Opt*	30 percent minimum	Opt
Supply air heat gain	No	Yes	Yes
Interior zone reheat	Yes	Yes	No
*Opt = Optimized for 7.62 E-04 m^3/s/m^2 (0.15 cfm/sf) (CA Title-24)			

Confirm that EnergyPlus has the capability perform the required calculations

The UFAD capabilities in EnergyPlus were developed with considerable effort by the research team under a previous project. [Bauman et al. 2006]. Comparisons with experimental data [Webster et al. 2008] verified the simulation results. Capabilities added to the user interface during this project facilitated a detailed hour-by-hour analysis of the results that checked the accuracy and by hand calculations and theoretical formulations (Appendix D). A study of component level energy quantities was conducted to verify the results obtained (Appendix E).

Demonstrate that the procedures to obtain needed data are clearly outlined.

Sensitivity runs (Figure 1) indicate that other than weather, there is little impact on performance due to window to wall ratio and internal load levels. These figures show results for Sacramento only, but are representative of results in other climates. Complete results for other climates are contained in a database that is part of Appendix G.

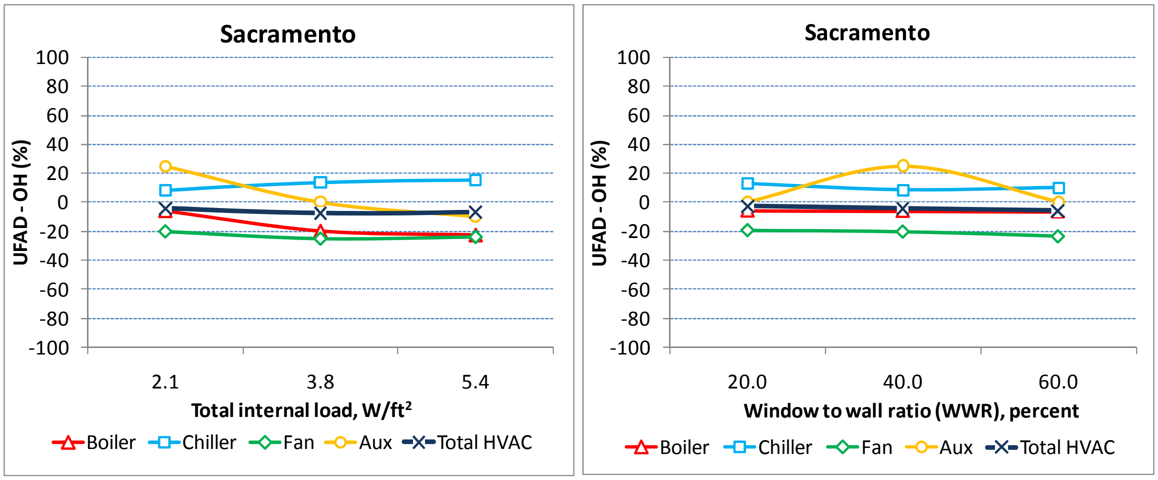

Figure 1. Example of sensitivity analysis for internal load and window to wall ratio.

Define metrics for stratification and comfort temperatures.

To allow a comparison of energy use between UFAD and OH, the research team has defined the concept of “equivalent comfort” for standing occupants in a stratified room as follows:

- The average occupied zone temperature ($T_{oz,avg}$), calculated as the average of the measured temperature profile from ankle level (0.1 m [4 in.]) to head level (1.7 m [67 in.]), is equal to the setpoint temperature.
- The occupied zone temperature difference (ΔT_{oz}), calculated as the head-foot temperature difference, is less than 3°C (5.4°F), as specified by ASHRAE Standard 55-2004.

To ensure equivalent comfort, the research team has adopted the following:

- Fix the stratification height to the standing person head height, 1.7 m (67 in.)
- Control the lower occupied zone is controlled to the same temperature as OH - 23.9°C (75°F).

Define metrics for energy reduction and DR response

The primary energy metric used is site-based annual HVAC EUI (kBtu/ft^2/yr). Two baseline cases for OH bracket the expected range of variation in performance yielded by typical design practice.

This study measures dynamic responses to DR activities using parameters of Peak Electricity Demand Reduction (PEDR) and Time-Averaged Electricity Demand Reduction (TAEDR) over the DR period. (See the definition of PEDR and TAEDR in Appendix H.) PEDR is the calculated result of a particular DR activity for a specific action. On the other hand, TAEDR shows the electricity consumption reduction due to DR averaged over daily or monthly time-scales. In most situations, PEDR is not equivalent to TAEDR because the transient thermal responses of a building are dynamic, so PEDR and TAEDR are considered separately.

For simplicity DR activities were implemented using a “Step Method” in which each DR activity was instantaneously triggered at the beginning of the DR period and returned back to normal operation at the end of the DR period. Sensitivity studies of PEDR and TAEDR reduction for a defined set of DR activities were performed at the same three California climate zones used in the energy performance studies; i.e., San Francisco (SF), Los Angeles (LA) and Sacramento (SC).

This study only considers DR activities for cooling during summer, June 01 – September 30, since typical California weather is hot in summer and mild in winter. Additionally, DR activities are only conducted on working days excluding weekends and holidays. As shown in Table 4, three DR time periods were used. The DR periods have the same end time, T_{DR}^{End}, but different start times, T_{DR}^{Start}, because the start time is considered to have a stronger relation to PEDR and occupant comfort. The baseline DR period starts at 12 pm and ends at 6pm. Delaying the start time resulted in shorter DR periods of 4 and 5 hours (Table 4).

Three DR activities were simulated; room set-point temperature adjustment (RSTA), interior lighting usage limit (LLT) and interior electrical equipment usage limit (ELT). The first DR activity, raising the RST, DT_{RST}^{DR} directly affects HVAC electricity demand (ED_{HVAC}) and occupant thermal comfort. Increased RST also heats the structural thermal mass during the DR period, causing additional cooling load after the DR period. Detailed schedules for DR activities are shown in Table 5.

Table 4. Time Duration of DR activities

	T_{DR}^{Start} *(hour)	T_{DR}^{End} *(hour)	Time Duration (hours)
ΔT_{DR}12_18 (Baseline)	12	18	6
ΔT_{DR}13_18	13	18	5
ΔT_{DR}14_18	14	18	4

*T_{DR}^{Start} is starting time and T_{DR}^{End} is ending time of DR

Table 5. DR activities

$\mathbf{DT_{RST}^{DR}}$ (C°)	Room Setpoint Temperature Adjustment (RSTA) during DR	$\mathbf{LMT_{light}^{DR}}$ **(LLT)**	Lighting usage (percent)	$\mathbf{LMT_{equip}^{DR}}$**(ELT)**	Equipment usage (percent)
0	24°C (75.2°F) (baseline)	0	100	0	100
1	25°C (77°F)	10	90	10	90
2	26°C (78.8°F)	20	80	20	80
3	27°C (80.6°F)	30	70	30	70
4	28°C (82.4°F)	40	60	40	60

1. DT_{RST}^{DR} : Difference of room set-temperature between baseline and DR (°C). 2. LMT_{light}^{DR} : percentage of lighting usage limit (percent) 3. LMT_{equip}^{DR} : percentage of equipment usage limit (percent)

The lighting usage limit, LMT_{light}^{DR} and the equipment usage limit, LMT_{equip}^{DR}, mainly reduce the building electricity demand (ED_{bldg}) which includes all electricity usage except HVAC. However, both reductions also involve ED_{HVAC} because lighting and equipment also emit heat and contribute to the internal cooling load (Table 2). Each DR action was simulated separately to determine the individual contributions.

To estimate the effectiveness of DR activities, this study uses two parameters, Peak Elect. Demand Reduction (PEDR) and TAEDR (Time Averaged Elect. Demand Reduction).

PEDR (Peak Electricity Demand Reduction). Reducing PED is a primary objective for DR actions. The proto-type building for OH and UFAD have different ranges of PED at the same time and location, and the PEDR is normalized for comparison as

$$PEDR = \frac{ED_{HVAC}^{DR}(t_{peak}^{DR})}{ED_{HVAC}^{NO}(t_{peak})}$$

where t_{peak} is time when ED_{HVAC}^{NO} is maximum, $ED_{HVAC}^{NO}(t)$ is the hourly-averaged electricity demand of HVAC energy consumption of normal operation (NO). The time $t_{peak}^{DR}$is the time when ED_{HVAC}^{DR} is maximum during DR and $ED_{HVAC}^{DR}$is the hourly-averaged ED of HVAC energy consumption during DR.

TAEDR (Time Averaged Electricity Demand Reduction over DR period). DR actions affect not only PEDR but also cooling energy over days or longer periods. This additional effect of DR was calculated from a time-averaged quantity over the DR period

$$\mathrm{TAEDR} = \int_{\mathrm{T_{DR}^{Start}}}^{\mathrm{T_{DR}^{End}}} \mathrm{ED_{HVAC}^{DR}(t)dt} \Big/ \int_{\mathrm{T_{DR}^{Start}}}^{\mathrm{T_{DR}^{End}}} \mathrm{ED_{HVAC}^{NO}(t)dt}$$

where $\mathrm{T_{DR}^{Start}}$ and $\mathrm{T_{DR}^{End}}$ are the start and end times, respectively. TAEDR represents percentage of energy consumption during DR compared to that of normal operation over the DR period

Weather categorization. Each location has different weather time series, so it is difficult to find general rules for responses of PEDR or TAEDR from daily or monthly results. Consequently, daily results are characterized in terms of ‘cool’ ‘warm’ or ‘hot’ weather (Table 6). Each location has different numbers of days within each weather category. SF has about 70 percent of ‘warm’ summer working days, while LA and SC have about 70 percent characterized as ‘hot’.

Table 6. Weather Categories, Cool, Warm & Hot

Weather categories	Range of $\mathrm{T_{ambient}^{day\ max}}$*
Cool	$\mathrm{T_{ambient}^{day\ max}}$< 23.9 °C (75 °F)
Warm	24 °C (75 F^{o})≤ $\mathrm{T_{ambient}^{day\ max}}$ ≤ 29.4 °C (85 °F)
Hot	$\mathrm{T_{ambient}^{day\ max}}$ > 29.4 °C (85.4 °F)

* $\mathrm{T_{ambient}^{day\ max}}$ is daily max. ambient temperature

Confirm that data have been collected in accordance with the simulation plan.

As evidenced by results shown in the following sections, all data anticipated in the simulation plan were collected.

Compare the energy usage between UFAD and OH systems for the variables under consideration.

The primary results for energy performance of UFAD systems are summarized in figures 2-5; a complete database of results is included with Appendix G in spreadsheet format. Key findings are as follows:

Comparison to OH baseline. Results for OHBC 1 and OHBC 2 (Figure 2) show the range of expected variation in OH system performance (Table 3). A detailed summary of the causes of the differences between these two cases is shown in Figure 5 of Appendix G. Figure 2 shows the performance of UFAD for three different AHU supply air temperatures compared to the two OH baselines for three different climates. These results indicate that UFAD operating at a fixed SAT = 13.9°C (57°F) performs slightly better than OHBC 1 and better than OHBC 2 for all SAT cases.

Air handling unit supply air temperature (AHU SAT). AHU SAT is a key design (and operating) parameter that drives the performance of UFAD systems. The hypothesis was that in mild climates like SF, cooling energy and fan energy would “trade off” and make it difficult to determine the most energy efficient operating condition for all cases. Figure 2 indicates why this is the case. Cooling energy decreases with increasing AHU SAT due to increased economizer use, but fan energy increases due to higher required airflow quantities. Heating energy also increases with increased SAT due to increased heating at the AHU on cold days to meet the

AHU SAT set point. The net result is increasing energy consumption with increasing SAT for all three climates. However, closer inspection reveals (not shown) that the total fan plus cooling energy actually decreases for SF but increases for LA and SC with increased SAT. Increased heating drives total energy consumption for SF while it has less impact in the warmer climates (since combined fan and cooling increases with SAT for these climates). Hence, optimizing performance by employing, e.g. reset strategies (see recommended future studies) may produce different results depending on climate, may require more complex control strategies than those typically used, and may require climate dependent solutions.

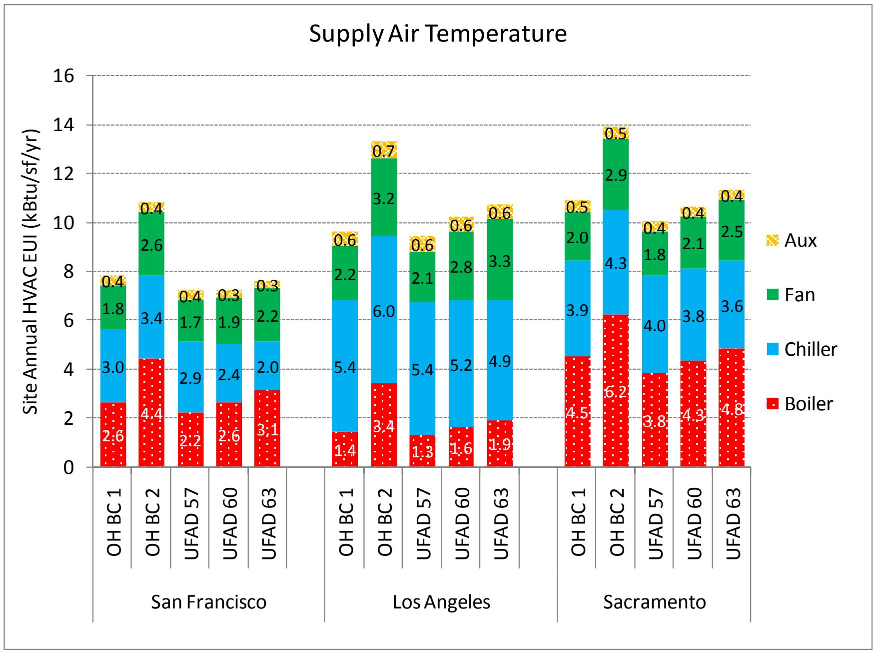

Figure 2. Impact of AHU supply air temperature in three climates

Table 7 shows UFAD energy savings relative to the two overhead baselines. Positive numbers indicate UFAD saves HVAC energy relative to OH while negative numbers show that OH performs better than UFAD. Note the large range of savings between the two OH baselines.

Table 7. Summary of UFAD HVAC EUI and percentage differences

	SF			**LA**			**SC**		
OHBC 1	**57°F**	**60°F**	**63°F**	**57°F**	**60°F**	**63°F**	**57°F**	**60°F**	**63°F**
Total HVAC kBtr/ft^2/yr	0.6	0.6	0.2	0.2	-0.6	-1.1	0.9	0.3	-0.4
Total HVAC	7.7 percent	7.7 percent	2.6 percent	2.1 percent	-6.2 percent	-11.4 percent	8.3 percent	2.8 percent	-3.7 percent
OHBC 2	**57°F**	**60°F**	**63°F**	**57°F**	**60°F**	**63°F**	**57°F**	**60°F**	**63°F**
Total HVAC kBtr/ft^2/yr	3.6	3.6	3.2	3.9	3.1	2.6	3.9	3.3	2.6
Total HVAC	33.3 percent	33.3 percent	29.6 percent	29.3 percent	23.3 percent	19.5 percent	28.1 percent	23.7 percent	18.7 percent

Supply distribution ductwork. Differences in supply ductwork configurations for UFAD systems are represented by differences in supply fan design static pressure. Pressures between 0.5 and

1.125 kPa (2 and 4.5 iwc) represent the range of variation in design pressure due to distribution ducting differences.[2] These differences range from efficient design with no distribution ducting, to partially ducted systems, such as air highways, to fully ducted systems. A fan static pressure increase from 0.5 to 1.125 kPa (2 to 4.5 iwc) causes fan energy to increase by 60 percent while total HVAC EUI increased by 11.1 percent (Figure 3). The fan energy shown in Figure 3 represents the combined total fan energy including supply, return, and perimeter terminal units. Supply fan design power increases by 32.8 kW, or 124.7 percent over this range. (The corresponding difference between UFAD (SAT = 13.9 °F [63°F], 0.75 kPa [3.0 iwc]) and OH (SAT = 13.9 °F [63°F], 1.125 kPa [4.5 iwc]) baselines, respectively is 5.6 kW or 14 percent)

UFAD system configurations. Figure 4 shows results for two UFAD system configurations compared to the UFAD baseline (supply plenums in series):

- Fully ducted – ductwork in the supply plenum supplies air directly to each interior and perimeter zone without passing through the plenum. This represents an ideal case without thermal decay in the supply air since heat transfer to the ductwork was not included, and without supply fan design pressure required to supply a ducted system (i.e., shows the impact of thermal performance only).
- Parallel supply plenums – all zones supplied in parallel, assuming distribution via ducts that supply perimeter zones directly from the AHU.

Only the ducted system has a significant impact on performance compared to the baseline (Figure 4). Since the ducted option does not include the extra static pressure required, the fan energy component is artificially low. Simulation results shown in Figure 4 are intended to illustrate the thermal performance impact of various ducting levels; the combined impact of static pressure requirements and thermal performance can only be simulated for fully ducted systems, which will be the subject of future work.

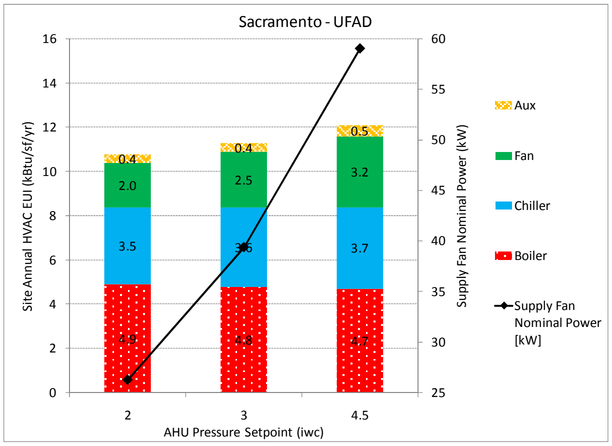

Figure 3. Impact of supply fan design static pressure for UFAD systems (3.0 iwc = baseline)

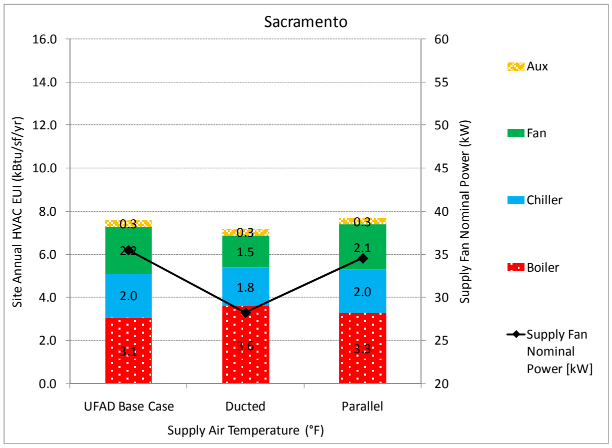

Figure 4. Impact of UFAD system configurations on thermal performance

Sensitivity of UFAD performance to stratification. Stratification should have a significant impact on performance by reducing the airflow required to cool the occupied zone (see Appendix D). To

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[2] Not including supply main shafts

study this impact, stratification was increased first by increasing the number of diffusers[3], and secondly by creating a fixed, high degree of stratification (Figure 5). Surprisingly, there is no significant impact from increasing the number of diffusers because of the limited capacity of swirl diffusers to lower throw height and thereby increase stratification to levels that influence performance. The fixed stratification (Fixed Phi=0.4[4]) case, however, indicates that it is possible to impact performance if aggressive measures are taken to increase stratification.

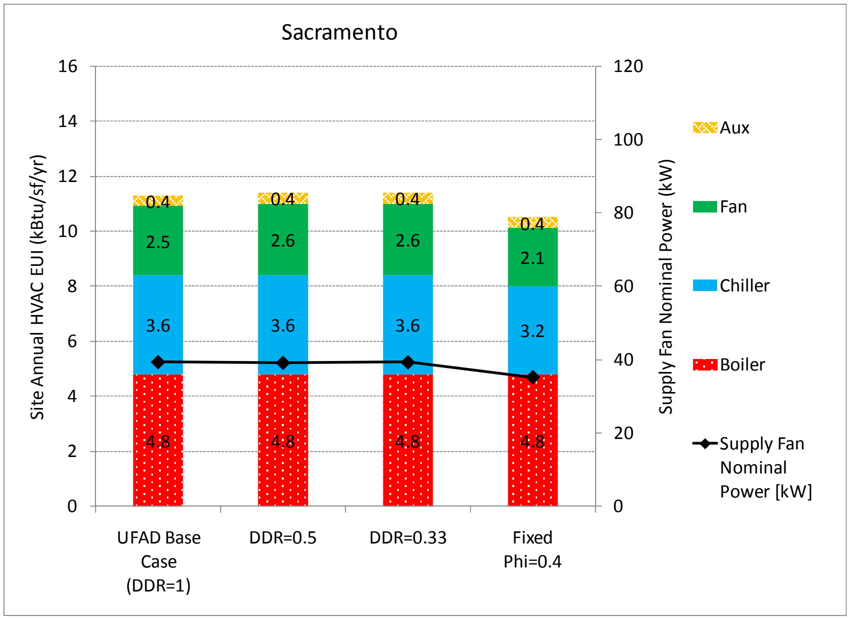

Figure 5. Impact of stratification in UFAD systems.

Check that desired stratification and comfort conditions are achieved, and determine any ranges of non-compliance.

Comfort conditions were checked by evaluating the computed temperatures in each zone for the year to ensure that system sizing and controls resulted in minimizing the hours of temperatures not met. Stratification was assumed to be acceptable if it was in the range of ASHRAE Standard 55; i.e., 3°C (5°F).

Demonstrate the effectiveness of different DR strategies

OHBC 1 and UFAD baseline were used for the energy performance analysis, with a WWR = 0.4 and internal load #1; these were also used as the baseline for DR. Applying the DR actions (Table 5), the responses of $\mathrm{ED}_{\mathrm{HVAC}}$, PEDR and TAEDR, the latter two averaged over the whole or weather-categorized summer weekday periods from June to September, were calculated.

Dynamic responses of ED_{HVAC}. The dynamic responses of $\mathrm{ED}_{\mathrm{HVAC}}$ of various DR actions are given in Appendix H. Figures 1a and 1b in App. H show that all actions reduce the HVAC energy demand during DR. Increasing the room setpoint (RST) also reduces HVAC demand both

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[3] Increasing the number of diffusers decreases the diffuser design ratio (DDR), the ratio of actual flow rate to manufacturers' nominal design flow rate.

[4] Phi represents the ratio of heat gain in the occupied zone to that for the entire room; i.e., 0.4 indicates that 40% of the total heat gain goes to the lower layer/occupied zone of the room.

during DR but also outside this period unlike equipment and lighting reductions, as a result of long-term heat transfer through building. Detailed discussions are included in Appendix H.

Whole summer weekday averaging. The simplest method for measuring DR effectiveness is to time average over whole summer weekdays. The TAEDR and PEDR curves caused by room setpoint temperature adjustment (RSTA), show steep decreasing trends for both OH and UFAD in all three climates (Figures 2a and 2c in App. H), which indicates that RSTA is effective for reducing $\mathrm{ED_{HVAC}}$ HVAC electric demand for all climate zones and HVAC modes. In hot climates (LA and SC) similar reductions of TAEDR and PEDR occur but UFAD decreases more than OH, indicating that increases in room setpoint temperature provides a higher reduction in demand in UFAD systems. In the more temperate climate of SF there is an even larger reduction in PEDR, as the opportunity for economizer action is greater due to the cooler climate.

Assuming the maximum in terms of occupant comfort is $\mathrm{DT_{RST}^{DR}} = 4$ (RSTA 28°C (82.4°F)) the TAEDR and PEDR decrease to less than 70 percent for OH and 60 percent for UFAD. The differences between OH and UFAD are negligible in SF but are significant in both SC and LA, due to the relatively mild SF summer, where the maximum outdoor temperature on most summer weekdays is below the RST 24°C (75°F). Hence, during DR periods cooling energy is only used to remove the internal heat load, allowing for more economizer usage.

ΔTAEDR and ΔPEDR, the differences of TAEDR and PEDR between OH and UFAD, respectively, between both systems match well with RSTA (Figure 1b in App. H). These results are consistent for the similar weather trends in LA and SC (Figure 5a, App. H). ΔTAEDR has peak values, ~7 percent, when RSTA ~26°C (78.8°F). ΔPEDR is larger than ΔTAEDR, showing that increasing the RST in a UFAD system reduces the peak energy demand (Figure 2d, App. H). The reductions in peak demand are greater for UFAD than for OH in these hot conditions.

Both TAEDR and PEDR decrease (Figures APH 2e and APH 2f) as the length of the DR period is reduced. This improvement in energy reduction seems to be associated with additional thermal mass cooling. TAEDR and PEDR decrease by about 4 percent by delaying DR activity from 1200 to 1400. However, DR periods should not start later than 1500 because more than 50 percent of summer weekdays for OH and 60 percent for UFAD have the peak electricity demand at 1500 (Figure APH5b for peak load time in Californian climates). In contrast to increasing the RST, reductions in lighting and internal load, have little impact (< 1 percent) (Figures APH 3e~3f and APH 4e~4f).

TAEDR and PEDR of LLT decreases up to 86 percent and 84 percent, respectively (Figures 3a and 3c, App. H). UFAD has larger reductions in TAEDR and PEDR compared to OH by 2 and 3 percent, respectively in LA and SC (Figures 3b and 3d, App. H). In SF, UFAD is less effective than OH for all levels of LLT. As the length of the DR period is reduced, both TAEDR and PEDR slightly increase (< 1 percent) (Figures 3e and 3f, App. H). DR responses of ELT are similar to that of LLT (Figures 4a~4f, App. H).

Table 8. PEDR performance matrix at ΔT_{DR}12_18

PEDR (percent)	DT^{DR}_{RST} (°C)						LMT^{DR}_{Light} (percent)					
	LA		**SF**		**SC**		**LA**		**SF**		**SC**	
	OH	UF	OH	UF	OH	UF	OH	UF	OH	UF	OH	UF
100	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
90	**0.81**	**0.53**	**0.47**	**0.4**	**0.74**	**0.47**	**37**	**34**	**23.5**	**26**	**35**	**28.5**
80	**1.91**	**1.21**	**1.03**	**0.89**	**1.68**	**1.05**	**>40**	**>40**	**>40**	**>40**	**>40**	**>40**
70	**3.67**	**2.16**	**1.73**	**1.58**	**3.06**	**1.89**	**>40**	**>40**	**>40**	**>40**	**>40**	**>40**
60	**>4**	**3.57**	**2.68**	**2.78**	**>4**	**3.34**	**>40**	**>40**	**>40**	**>40**	**>40**	**>40**

(values are obtained by quadratic interpolation of data in Figures APH 2c, APH 3c and APH 4c)

Table 9. PEDR performance matrix at ΔT_{DR}12_18

PEDR (percent)	LMT^{DR}_{Equip} (percent)					
	LA		**SF**		**SC**	
	OH	UF	OH	UF	OH	UF
100	**0**	**0**	**0**	**0**	**0**	**0**
90	**44**	**43**	**28**	**32.5**	**42**	**36**
80	**>50**	**>50**	**>50**	**>50**	**>50**	**>50**
70	**>50**	**>50**	**>50**	**>50**	**>50**	**>50**
60	**>50**	**>50**	**>50**	**>50**	**>50**	**>50**

The DR performance matrix (Tables 8,9 and Table 1 of App. H) summarizes the effectiveness of OH and UFAD, showing that RSTA is the most effective DR strategy. To achieve 90 percent PEDR requires less than 1°C (1.8°F) increase in setpoint temperature, but ELT or LLT load reductions need to be larger than 30 percent. Furthermore, UFAD setpoint increases are lower than OH. The required ELT to satisfy a given PEDR or TAED is larger than LLT since the convective heat transfer of equipment is smaller than that of lighting (Table 2).

Weather categorized summer weekdays averaging. Each location has different weather trends over summer. Most summer weekdays in SF are categorized as ‘cool’ while the majority of LA and SC summer days are classified as ‘hot’ (Figure 5a, App. H). The appropriate DR action depends on the maximum external temperature. The peak ED_{HVAC} timing is related to minimizing PEDR and TAEDR during DR.

The PEDR curves of OH and UFAD at both LA and SC match well on ‘warm’ and ‘hot’ days (Figures 6 and Figure 5a, App. H). These curves provide general behavior in warm, dry climates. PEDR or TAEDR results for ‘cool’ days at LA or SC are inconsistent and have no relation to the ‘warm’ or ‘hot’ day results, possibly since less than 5 percent of summer weekdays are classified as ‘cool’, so that the statistical sample is small. At LA and SC, the PEDR of UFAD on ‘hot’ days is about 3 percent below that of ‘warm’ days when DT_{RST}^{DR} = 2 and 5 percent when DT_{RST}^{DR} = 4. Thus UFAD is particularly effective at reducing peak demand in hot climates. TAEDR shows similar results to PEDR (Figures 6c and 6d, App. H).

The differences between UFAD and OH, ΔPEDR and ΔTAEDR, are maximum on ‘hot’ days and the optimized DT_{RST}^{DR} is 2°C (3.6°F) (RSTA 26°C (78.8°F)) at LA and SC and 1.5°C (2.7°F) (RSTA 25.5°C (77.9°F)) at SF (Figure 7). Weather categorized results for lighting and equipment DR reductions are similar to the whole-summer averaged results and show less sensitivity to the weather categories (Figures 7a, b and 8a, b, App. H). The difference in PEDR or TAEDR between OH and UFAD is less than 3 percent and similar for different weather categories. These similarities imply that DR activities that reduce the convective heat transfer of internal loads are not influenced by weather conditions.

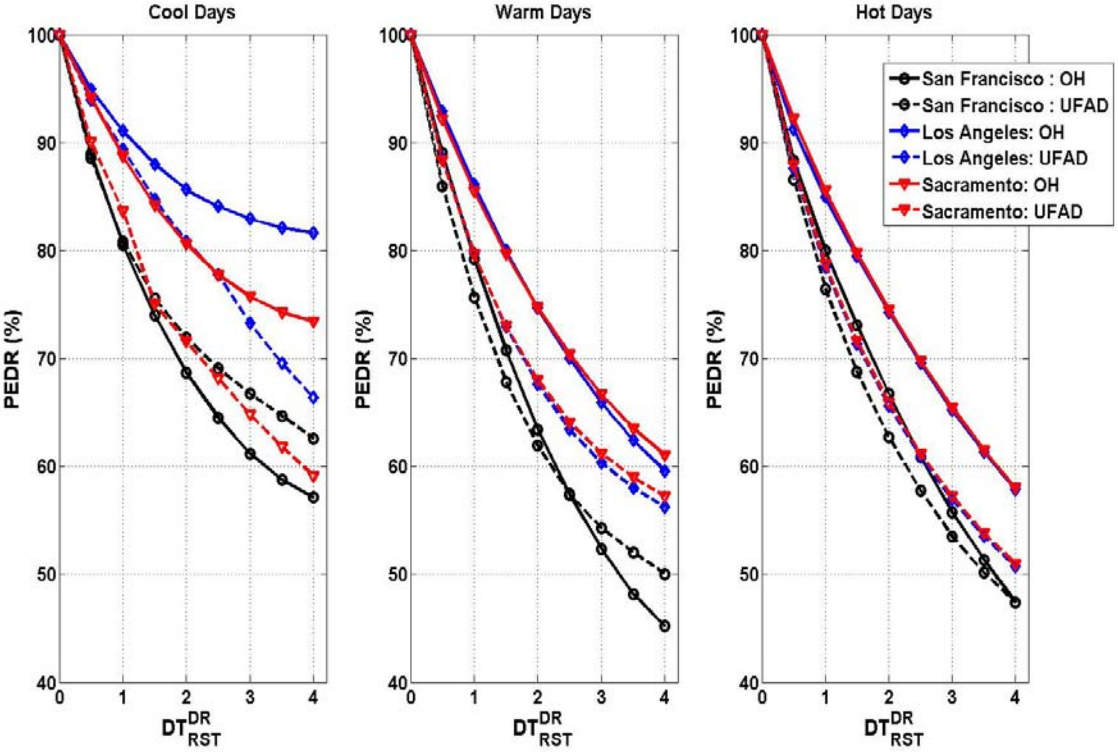

Figure 6. Weather categorized PEDR on RSTA

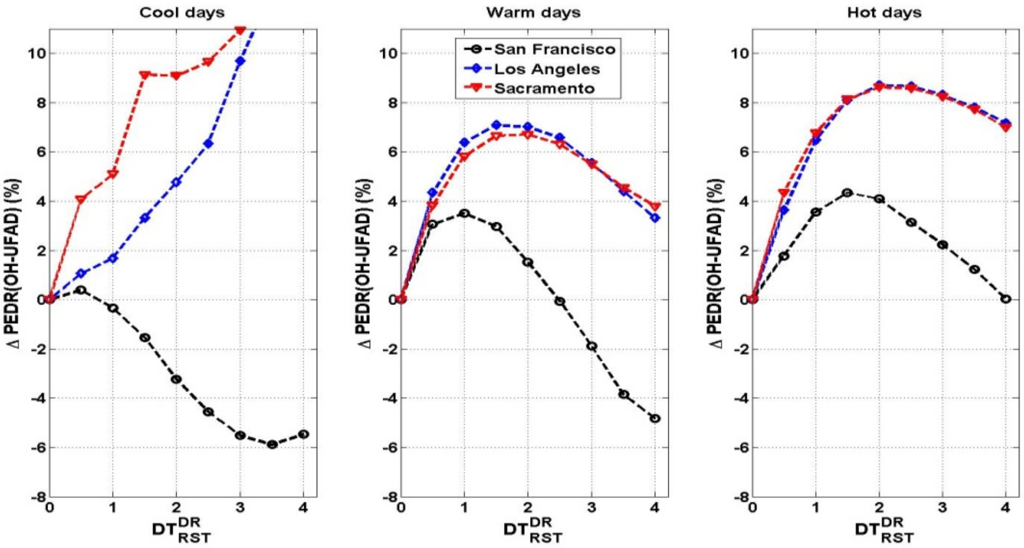

Figure 7. Difference of Weather categorized PEDR between OH and UFAD on RSTA

<u>Implement modifications to the UFAD model within EnergyPlus to account for deficiencies revealed in the results.</u>

Refinements to UFAD simulation models. UFAD modeling improvements made for this project included the following (See Appendix F for details):

- Revisions to the correlations used to simulate the effect of stratification by dividing the room heat gain between upper and lower layers in the room for interior zones.
- Development and addition of stratification correlations for perimeter zones.
- Refinements in the diffuser characteristic properties for both interior and perimeter zones.

Modifications to account for deficiencies revealed in the results. The following modifications were made to correct deficiencies found during preliminary simulations.

- AHU Fan sizing –EnergyPlus auto-sizing routines result in properly sized AHU fans for OH, but they usually cause UFAD fans to be oversized. A modification was implemented to size the fans automatically using a one-month pre-simulation to find peak fan airflow (typically a summer month). The peak airflow was selected and the sizing factor of 1.2[5] applied to size the AHU fan for the real run.
- Central chiller sizing – Similar to the AHU fan sizing, a modification was implemented to to avoid over-sizing the UFAD chiller. A one-month simulation was run and the UFAD chiller sized based on the peak chiller cooling rate among the one-month hourly data using a sizing factor of 1.0.

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[5] A 20 percent over sizing is a somewhat arbitrary factor but represents typical practice of adding safety factors to design specifications. However, normally this safety factor would be applied to a more conservative block load calculation. The intent here is to provide a consistent method of sizing between all runs. Further research is needed to understand the impact of sizing assumptions for UFAD systems and to develop appropriate sizing algorithms.

- Ventilation minimum airflow – It is not possible to specify the minimum airflow rate of each VAV box in EnergyPlus. To overcome this limitation, peak design airflow results from a one-month simulation were saved for ach VAV box. Minimum fractions of each VAV box corresponding to the ventilation requirement (7.62 E-04 $m^3/s/m^2$ [0.15 cfm/sf]) were calculated and used as input for the annual simulation. Therefore, the minimum airflow was set automatically to be 7.62 E-04 $m^3/s/m^2$ (0.15 cfm/sf) for every VAV box.
- Perimeter air terminal unit (ATU) sizing –the perimeter ATU fans are oversized by auto sizing. Therefore, the same work around was implemented to size perimeter ATU units.

Implement and test modifications in the capabilities of EnergyPlus to model practical situation

Modifications to model practical situations. The following modifications were made to EnergyPlus/UFAD to attempt to include situations that occur in real systems.

- OH duct heat gain – Models in EnergyPlus do not account for supply-duct heat gain, leading to poor comparisons to UFAD. A modification making a fictitious zone in the input file which did not to affect the prototype building was made. The inlet air node of the fictitious zone was connected to the AHU outlet node and the outlet node of the fictitious zone was connected to the inlet to each VAV box. In addition, a constant heat gain (via an occupancy load) was modeled in the fictitious zone so that a (variable) temperature rise was applied (in the range of 0.5~1.2 °C [1~2 °F]) thereby providing a rough simulation of duct heat gain.
- Variable speed fan part load curves – Care must be exercised to specify part load operation of variable speed fans including accurate specification of fan design parameters and application of appropriate sizing and part load strategies depending on the type of comparisons that are intended. Appendix F contains details of the procedures used in this project.

Determine the potential benefits in different climatic zones and for different DR strategies

Table 10 summarizes the energy savings benefits for the three climates studied. These represent the maximum potential for HVAC system energy consumption savings based on a comparison between UFAD and overhead systems. The climate zones represent the largest metropolitan areas for California as well as the locations where UFAD is most likely to be used.

Table 10. Summary of potential energy savings benefits

	SF	**LA**	**SC**
OHBC 2	**57°F**	**57°F**	**57°F**
Total HVAC kBtr/ft^2/yr	3.6	3.9	3.9
Total HVAC	33.3 percent	29.3 percent	28.1 percent

Table 11 represents peak demand reduction of a DR strategy, RSTA, which is proven to be most effective DR strategy for the three climate zones compared to ELT or LLT. Potential peak demand reductions are shown in all the climate zones and higher PED reductions in LA and SC (both cities has relatively hot summer days compared to SF) support that UFAD has its strength to reduce PED compared to OH on relatively hot summer day in which maximum of PED is required during peak load period.

Table 11. Summary of DR savings : “Hot Day” weather categorization, DR period (12pm-6pm)

	SF	LA	SC
OHBC 1	**57°F**	**57°F**	**57°F**
Room setpoint temperature (Normal operation)	**75.2 °F**	**75.2 °F**	**75.2 °F**
Room setpoint temperature adjustment (DR operation)	**78.8 °F**	**78.8 °F**	**78.8 °F**
PEDR (%) savings of UFAD	**4.1 %**	**8.7 %**	**8.6 %**

Determine the best venues to disseminate the results of this study and any tools developed to the industry.

There are three paths to reach practitioners that could use the tools and procedures developed during this project. First, the researchers anticipate that the whole building model template will be disseminated through the DOE EnergyPlus simulation suite in an upcoming release. Secondly, a UFAD simulations toolkit will be disseminated directly to the group of practitioners who are partners of the Center for the Built Environment (CBE) via the CBE website and workshops. Finally, these tools will be used in a project being done by the authors to support development UFAD modeling capabilities in the ACM procedures for Title 24.

Conclusions

Interface DOE prototype large commercial office building with Design-Builder

Experiences in the project have shown that complex models need to be developed from scratch or from well established templates provided by EnergyPlus; attempting to use interface tools that auto-generate input files turned out to cause more problems than anticipated. The final model (the CBE Whole-building Prototype, or CBE Prototype) was based on a complete revamping of the input structure better suited to the needs of this project.

Modify IDF file to include UFAD features and by developing “user interface” assistance tools

User interfaces aimed at simplifying the input requirements and facilitating parametric runs proved to be extremely useful and are highly recommended. The EnergyPlus input structure is very complex and prone to error when parameters are changed; the macro file capability is essential to mitigate errors. Output processors configured to show results in a logical way are extremely important to debugging. Results analysis tools are likewise considered essential to organizing the large number of files and creating analysis charts and tables.

Specify matrix to cover range of desired scenarios, for UFAD and OH comparison and DR response of UFAD.

A run matrix aligned to cover the range of runs necessary to support the objectives is important but researchers should be aware that many more runs are necessary to explore problems and debug EnergyPlus routines and modeling problems. Several hundred runs were necessary to accomplish the objective of this project.

Confirm that EnergyPlus has the capability perform the required calculations

EnergyPlus certainly has the capability to accomplish the required calculations although several problems prevented completion of some secondary objectives and resulted in adding considerable analysis time.

Demonstrate that the procedures to obtain needed data are clearly outlined.

Even the most perfect research plan cannot anticipate the issues that will come up; the overall plan for this project was adequate for achieving final objectives but had to be modified to accommodate the unanticipated problems.

Define metrics for stratification and comfort temperatures.

The output processing tools incorporated means to evaluate these parameters easily.

Define metrics for energy reduction and DR response

It was necessary to define new metrics for DR, based on different measures of peak load reduction. However, standard energy metrics were used for consumption studies.

Confirm that data have been collected in accordance with the simulation plan.

No problems were encountered with collected data necessary to meet the objectives.

Compare the energy usage between UFAD and OH systems for the variables under consideration.

Energy performance of UFAD systems was measured by comparing simulation results to two state-of-practice overhead systems for three California climates. A summary of outcomes follows:

- Energy consumption of UFAD systems is sensitive to climate but not to other building design variables of window to wall ratio and internal load.
- Within all climates, optimum energy performance for UFAD systems occurs at AHU supply temperatures equivalent to those of OH systems, 57°F. At this optimum temperature, UFAD energy savings ranged from 7.7-33.3 percent for SF, 2.1-29.3 percent for LA, and 8.3-28.3 percent for SC.
- Simulations to estimate the impact of different UFAD distribution ductwork configurations resulted in fan energy increases of 60 percent over a design static pressure range of 0.5 to 1.125 kPa (2 to 4.5 iwc), representative of design with no supply distribution ductwork to a fully ducted system.
- Simulations to estimate the impact on thermal performance of different plenum supply configurations showed that only a fully ducted version resulted in improved HVAC energy performance.
- For diffuser products typical of today’s practice, the benefits of stratification could not be realized by adding more diffusers. However, simulations with idealized stratification indicate that measures to increase stratification by yet unknown means hold promise of improving HVAC performance by 7.1 percent.

Contrary to expectations of researchers, UFAD overall HVAC performance (based on site EUI) was best when operated with air handler supply air temperatures (SAT) equal to that of OH systems (57°F) for all climates studied. For AHU SAT= 57°F , UFAD outperformed OH in three climates by 7.7-33.3 percent (SF), 2.1-29.3 percent (LA), and 8.3-28.1 percent (SC) when compared to "good" practice and "standard" practice overhead systems, respectively.

Differences in the amount of supply distribution ductwork (from no ductwork to fully ducted) can have a significant impact on fan energy consumption. However, the thermal performance impact of supply ductwork configurations (series, parallel, ducted) has very little impact on UFAD HVAC energy consumption.

Improved UFAD energy performance with increased stratification is not easily realized using state of practice diffusers, but a savings of 7.1 percent was predicted for idealized stratification indicating some potential for improving the performance of these systems in the future.

Check that desired stratification and comfort conditions are achieved, and determine any ranges of non-compliance.

Equivalent comfort for UFAD and OH was ensured by controlling the occupied zone to the same temperature. Zone comfort conditions were checked using a computation of hours that temperatures not met in each zone (via the output processor). Minor differences between OH and UFAD occurred in interior zones since UFAD systems have no heating in these zones.

Demonstrate the effectiveness of different DR strategies

The effectiveness of DR actions for the baseline building was compared between OH and UFAD for the three Californian climate zones and the following were concluded:

- Increasing the room setpoint temperature provides higher energy savings and peak demand reduction than reducing equipment or lighting loads.
- There is a small (5 percent) advantage in reducing lighting rather than equipment consumption for both the average energy and the peak energy reduction.
- There are slight improvements in terms of the normalized average energy and peak energy consumption by delaying the start of the DR period. The main benefit (4 percent) is again increasing the setpoint temperature, with minimal impact of reducing equipment or lighting loads.
- The similarities of ELT and LLT differences in PEDR or TAEDR between OH and UFAD among the weather categories imply that DR activities reducing convective heat transfer of internal load are not influenced by weather conditions
- UFAD produces reductions in average energy and peak demand over a DR period compared to OH by approximately 6~10 percent when the setpoint temperature is higher than 26°C (78.8°F).
- Increasing room setpoint temperature is most effective as a DR action on 'hot' (> 29.4°C (85 °F)) days.

The effectiveness of DR actions on baseline-building configurations of OH and UFAD, with a specified internal load configuration (Internal Load #1) for three different climate zones was examined. Increasing room set point shows higher energy savings and peak demand reduction compared to equipment and lighting load reductions, and UFAD is more effective compared to OH on LA and SC where higher electricity demands are needed during summer. In practice, the improved DR effectiveness of UFAD provides improved occupant thermal comfort and achieves better electricity demand reduction than OH.

Implement modifications to the UFAD model within EnergyPlus to account for deficiencies revealed in the results.

Workaround procedures for sizing fans, chillers, and terminal units were required to ensure accuracy in the simulations. Several issues remain unresolved (e.g., variable area terminal unit, issues with controlling the variable speed ATU in the deadband) and await programming changes by EnergyPlus developers. These changes will affect the results but are not expected to change the basic conclusions.

Implement and test modifications in the capabilities of EnergyPlus to model practical situations

Modifications to EnergyPlus were focused on refinements to UFAD input parameters to more accurately simulation stratification with different diffuser types.

Determine the potential benefits in different climatic zones and for different DR strategies

The results show that annual energy savings of UFAD compared to OH are positive and depend on the climate zone. Maximum savings of HVAC energy consumption of 33.3, 29.3, and 28.1 percent were shown for SF, LA, SC, respectively. The calculations also show significant reductions in peak demand (4.1, 8.7 and 8.6 percent for SF, LA and SC respectively) compared to conventional systems. These savings are especially beneficial in the warmer climate zones.

Determine the best venues to disseminate the results of this study and any tools developed to the industry.

The venues for dissemination of the simulation tools developed in this project are already well established and work is being done by the research team to refine and simplify users ability to conduct a wide variety of studies. Venus are outlined in the Outcomes section.

Commercialization of UFAD technology is well established. It is routinely considered in decisions about HVAC technology. Although promotions in the past overestimated the performance benefits it still has a number of compelling features that continue to favor it.

Commercialization of the simulations tools may be facilitated by the work on this project but these developments will be publically available to users free of charge via the dissemination paths outlined above. Commercialization would most likely focus on incorporating the capabilities within commercial simulation suites or developing better user interfaces.

Recommendations

Outlined below is “follow-on” work that would extend the present study to advance UFAD technology by determining optimum design and operation.

Future work

Optimization studies

- Chiller leaving water temperature reset – Implement reset of chilled water supply temperature to investigate the impact on cooling energy differences for UFAD and OH.
- AHU SAT reset – Investigate the impact of reset to manage loads not met under high thermal decay conditions. This should be combined with study for startup conditions to mitigate cooling temperatures not met in the morning after a warm summer night. At present there are one or two hours where temperatures are not met due to peak startup loads. Night cycling also needs to be repaired to mitigate startup peaks compared to not running at night.
- AHU bypass – To hold humidity and perhaps provide better cooling coil sizing and modeling, study impact of newly installed AHU return air bypass algorithm.
- Core zone heating and minimum volume issues – UFAD systems have no heating in core zones which, for rooftop zones, can cause overcooling. This will be exacerbated by too high a minimum for ventilation of these zones
- Do sensitivity study with various VAV minimums to gauge the impact on comfort and energy.
- Plenum leakage – Add factors to simulate typical leakage effects.
- Slab insulation – Investigate performance impact of insulating underfloor plenum slabs to reduce heat gain from return plenum below.
- Raised floor insulation – Insulate raised floor to reduce heat gain from above.
- Optimized DR manager – Provide enhanced controls to maximize electricity demand reduction while minimizing occupant thermal discomfort.

Recommended EnergyPlus changes and improvements

Following is a list of modification that would overcome a number of obstacles encountered during this project and represent limitations for future simulation studies with EnergyPlus.

- Sizing improvements – Serious HVAC sizing issues were encountered, especially with UFAD systems; these need to be improved so that default sizing parameters deliver reliable and consistent results. This includes consideration for the impact on design ATU supply temperature caused by plenum thermal decay.
- Perimeter zone model – Repair perimeter zone variable speed model to allow fan to be on during the dead band if desired or to allow for minimum flow due to leakage through the ATU.
- UFAD B system models – Add new terminal unit algorithm that represents state of practice for this system type.
- Window blinds control – Provide improved blinds control.
- Night cycle controls – Repair bug that prevents HVAC system operation at night when needed

- Demand limit manager - Provide DR controller responding to various parameters such as outdoor temperature, occupant thermal comforts(i.e. Fanger Predicted Mean Vote value) and etc. Allow user-defined DR strategies upon various DR activities.

Public Benefits to California

Evaluate the Benefits to California Electric Ratepayers

Energy benefits

Table 12 summarizes the results of benefits calculations for the large office segment of the California building stock derived from CEUS end use analyses [Itron 2006]. Energy benefits are shown for a 10 year period starting in 2010 to account for expected increases in market penetration of UFAD systems. Table 10 is based on savings in HVAC energy only, which is the focus of this project; at the building level these savings will be much less. CEUS data HVAC EUIs are the sum of the statewide values for heating, cooling, and ventilation components for large commercial offices. The UFAD EUI percentage savings is an average of the values for all three climates studied for OHBC 2 in Table 7 for the optimum SAT case of 57°F.

Table 12: California UFAD HVAC energy savings potential

	2010	**2015**	**2020**							
Years out, UFAD	**11**	**16**	**21**							
Years out, Stock	**4**	**9**	**14**							
Building growth rate, sf per year	**2%**	**2%**	**2%**							
UFAD penetration rate	**12.6%**	**19.1%**	**25.6%**							
Stock Base yea r= 2006 UFAD penetration base year = 1999	**Large office**									
New Construction Equivalent	UFAD HVAC Savings, %	HVAC EUI Base kBtu/sf/yr	Bldg stock floor area 10^6 SF	2010 UFAD savings, kBtu/yr	HVAC EUI Base kBtu/sf/yr	Bldg stock floor area 10^6 SF	2015 UFAD savings, kBtu/yr	HVAC EUI Base kBtu/sf/yr	Bldg stock floor area 10^6 SF	2020 UFAD savings, kBtu/yr
Total HVAC savings	30%	39.8	713.2	1073.2	39.8	779.3	1777.5	39.8	845.3	2584.4
Total HVAC				28393			31021			33650
UFAD savings, % of HVAC				3.8%			5.7%			7.7%

Assumptions made for these calculations are:

- Energy EUIs and floor area based on CEUS existing building data [Itron 2006] HVAC EUI is sum of statewide average for heating, cooling, and ventilation.
- Penetration rates based on raised access floor industry data [Reynolds 2005] extrapolated to the entire raised floor industry and divided by office construction area for new construction from Dodge. Thus the penetration is based on "equivalent new construction" volume since amount raised floor project going to retrofit projects is unknown. Retrofit performance is not assumed to be different than new construction.
- Building floor area is assumed to grow over time at 2 percent, but EUIs are assumed to be constant over time
- Does not assume differences in EUI for new vs. existing buildings
- UFAD savings = Floor area * EUI * penetration rate*UFAD EUI savings from Table 7

Estimates of maximum potential savings in UFAD HVAC energy on a statewide basis for large offices (the primary application for UFAD) showed savings of 3.8, 5.7, 7.7 percent for 2010, 2015, 2020 respectively as indicated in Table 12. These estimates assume penetration rates by UFAD in new construction only. Among the factors that could significantly affect these estimates are the following:

- Higher penetration rates in retrofits and other building types not estimated here
- Lower rates of adoption due to perceived problems with the technology and lower savings relative to other technologies.
- Cost considerations and developments that could improve its performance. (See recommendations for future work.)

Demand response benefits were not estimated; calculation methods were not identified and developing new methods is considered beyond the scope of this project.

Title 24

The requirements of California Title 24 Nonresidential Alternative Calculation Method (ACM) Approval Manual covers UFAD systems but there are no approved simulation programs that treat UFAD adequately other than EnergyPlus. The work of this project will facilitate the use of EnergyPlus to meet ACM requirements. Additionally, the work of this project will provide data that will be useful in setting priorities for code compliance programs.

Evaluate the effectiveness of various paths to reach consumers

The results of this study are being prepared for publication in ASHRAE Transactions. They will also be communicated to the industry at future meetings of the Center for the Built Environment at Berkeley. Preliminary results have been presented at CBE meetings in October 2008 and April 2009.

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Glossary

Name	Acronym	Definition
Air handling unit	AHU	Central fan sub-system
Air highways		Three sided duct whose top is the raised floor panel used to distribute supply air in underfloor plenums
Air terminal unit	ATU	Acronuym used in EnergyPlus to designate zone terminal units
Building electricity demand	$\mathrm{ED}_{\mathrm{bldg}}$	Electricity demand over a building excerpt HVAC related electricity demand
Center for the Built Environment	CBE	Industry-university partnership at UC Berkeley
Demand response	DR	Peak load response to demand limiting strategies
Diffuser design ratio	DDR	Ratio of actual airflow to design airflow for a floor diffuser
Energy use intensity	EUI	Annual energy use per unit floor area
Fan coil unit	FCU	Fan powered terminal unit (with heating coil) used for conditioning perimeter zones
HVAC electricity demand	$\mathrm{ED}_{\mathrm{HVAC}}$	HVAC related electricity demand over a building
Interior electrical equipment usage limit	ELT	Percentage of limited interior equipment usage over normal operation during DR period
Interior electrical equipment usage limit (Percentage difference)	$\mathrm{LMT}_{\mathrm{equip}}^{\mathrm{DR}}$	Percentage Difference between normal operation(100 percent of ELT) and ELT(percent)
Interior lighting usage limit	LLT	Percentage of limited interior lighting usage over normal operation during DR period
Interior lighting usage limit (Percentage difference)	$\mathrm{LMT}_{\mathrm{Light}}^{\mathrm{DR}}$	Percentage Difference between normal operation(100 percent of LLT) and LLT(percent)
Los Angeles	LA	
Peak electricity demand	PED	Peak electricity demand over daily operation

Peak electricity demand reduction	PEDR	Percentage of peak electricity demand reduction over normal operation due to DR activities
Room air stratification	RAS	
Room set-point temperature adjustment	RSTA	Room set-point temperature adjustment over DR period
Room set-point temperature adjustment (Temperature difference)	$\mathrm{DT}_{\mathrm{RST}}^{\mathrm{DR}}$	Temperature difference between RSTA and normal operational room setpoint temperture
Sacramento	SC	
San Francisco	SF	
Stratification height		Boundary between upper and lower layers in the room of stratified systems
Supply air temperature	SAT	Temperature of air at discharge of AHU or entering the room
Swirl diffuser	SW	Turbulent flow floor diffuser that achieves high induction via rotational flow (swirl)
Time-Averaged Electricity Demand Reduction	TAEDR	Percentage of time averaged electricity demand over normal operation due to DR activities
Underfloor air distribution	UFAD	
VA diffuser	VA	VAV floor diffuser characterized by variable discharge area and constant velocity discharge
Variable air volume	VAV	Method of controlling room temperature using variable airflow
Window to wall ratio	WWR	Ratio of window area to wall area for building facades

Appendix A- Large Office Prototype Construction Properties

Appendix B - Prototype Building Scorecards

Appendix C - Run Control Input/Output User Interface

Appendix D - Preliminary Confirmation of Results

Appendix E - Fan Energy Performance Simulation Methods

Appendix F - CBE EnergyPlus/UFAD Simulation Toolkit Users Guide

Appendix G - Energy Performance Study Results and Database

Appendix H - Demand Response Performance Results

California Energy Commission **Building Energy Research Grant (BERG) Program** **PROJECT DEVELOPMENT STATUS**	**Questionnaire**

Answer each question below and provide brief comments where appropriate to clarify status. If you are filling out this form in MS Word the comment block will expand to accommodate inserted text.

Please Identify yourself, and your project: **PI Name** __Paul Linden______**Grant** # 54917A/06-05B

Overall Status

Questions	**Comments:**
1) Do you consider that this research project achieved the goal of your concept?	*Briefly state why.* *Yes. We performed the analysis and were able to address the energy performance and demand response issues.*
2) Do you intend to continue this development effort towards commercialization?	*The focus of this project is using simulation software to study performance. The tool used, EnergyPlus, is already “commercialized”. Our role is to further its development and use it to conduct studies like these, which we will continue to do.*
Engineering/Technical	
3) What are the key remaining technical or engineering obstacles that prevent product demonstration?	*The “product” (UFAD version of EnergyPlus) has already been demonstrated. Further work on refinements and bug fixes as well as improvements in the user interface will facilitate broader use.*
4) Have you defined a development path from where you are to product demonstration?	*N/A*
5) How many years are required to complete product development and demonstration?	*N/A*
6) How much money is required to complete engineering development and demonstration?	*Uncertain, some money has already been allocated for further work.*
7) Do you have an engineering requirements specification for your potential product?	*N/A – this is not a hardware product*
Marketing	
8) What market does your concept serve?	*Large and small commercial buildings.*
9) What is the market need?	*There is a market need for validated energy simulation programs that can accommodate UFAD systems*
10) Have you surveyed potential customers for interest in your product?	*No*
11) Have you performed a market analysis that takes external factors into consideration?	*N/A*
12) Have you identified any regulatory, institutional or legal barriers to product acceptance?	*NA*
13) What is the size of the potential market in California for your proposed technology?	*NA – Our product is software not UFAD technology.*

14) Have you clearly identified the technology that can be patented?	*No – the results will be published in the open literature*
15) Have you performed a patent search?	*N/A*
16) Have you applied for patents?	*N/A*
17) Have you secured any patents?	*N/A*
18) Have you published any paper or publicly disclosed your concept in any way that would limit your ability to seek patent protection?	*NA - We are in the process of preparing our work for publication in the public domain*
Commercialization Path	
19) Can your organization commercialize your product without partnering with another organization?	*NA*
20) Has an industrial or commercial company expressed interest in helping you take your technology to the market?	*NA*
21) Have you developed a commercialization plan?	*NA*
22) What are the commercialization risks?	*NA*
Financial Plan	
23) If you plan to continue development of your concept, do you have a plan for the required funding?	*We are seeking funding for follow-on research*
24) Have you identified funding requirements for each of the development and commercialization phases?	*N/A*
25) Have you received any follow-on funding or commitments to fund the follow-on work to this grant?	*CEC multi-project contract includes UFAD simulation studies*
26) What are the go/no-go milestones in your commercialization plan?	*N/A*
27) How would you assess the financial risk of bringing this product/service to the market?	*N/A*
28) Have you developed a comprehensive business plan that incorporates the information requested in this questionnaire?	*NA*
Public Benefits	
29) What sectors will receive the greatest benefits as a result of your concept?	*Commercial*
30) Identify the relevant savings to California in terms of kWh, cost, reliability, safety, environment etc.	*See final report – identified benefits of technology studied, i.e., UFAD.NA to software "product" used for the study.*
31) Does the proposed technology reduce emissions from power generation?	*NA*
32) Are there any potential negative effects from the application of this technology with regard to public safety, environment etc.?	*No*
Competitive Analysis	

33) What are the comparative advantages of your product (compared to your competition) and how relevant are they to your customers?	*NA*
34) What are the comparative disadvantages of your product (compared to your competition) and how relevant are they to your customers?	*NA*

Development Assistance

The BERG Program may in the future provide follow-on services to selected Awardees that would assist them in obtaining follow-on funding from the full range of funding sources (i.e. Partners, PIER, NSF, SBIR, DOE etc.). The types of services offered could include: (1) intellectual property assessment; (2) market assessment; (3) business plan development etc.

35) If selected, would you be interested in receiving development assistance?	*NA*