DRAFT SUMMARY REPORT
OCTOBER 2006

UNDERFLOOR AIR DISTRIBUTION (UFAD) COST STUDY: ANALYSIS OF FIRST COST TRADEOFFS IN UFAD SYSTEMS

DRAFT FOR REVIEW (EXCERPT)

Tom Webster, Corinne Benedek,
and Fred Bauman

This draft report was submitted to the
U.S. General Services Administration (GSA)
Public Buildings Service Research Program.

For a complete copy of the report, or to serve as a reviewer, please contact the authors.

UNDERFLOOR AIR DISTRIBUTION (UFAD) COST STUDY: ANALYSIS OF FIRST COST TRADEOFFS IN UFAD SYSTEMS DRAFT FOR REVIEW

TOM WEBSTER
CORINNE BENEDEK
FRED BAUMAN

THE CENTER FOR THE BUILT ENVIRONMENT
UNIVERSITY OF CALIFORNIA, BERKELEY

SEPTEMBER 2006

PREPARED FOR:
U.S. GENERAL SERVICES ADMINISTRATION (GSA)
PUBLIC BUILDINGS SERVICE RESEARCH PROGRAM
CONTRACT NO: GS-00P-02-CYC-0071

CBE
CENTER FOR THE BUILT ENVIRONMENT

1 EXECUTIVE SUMMARY

This paper presents a discussion of first cost differences (premiums and savings) between a prototype commercial office building with underfloor air distribution (UFAD) and the same building with a conventional overhead (OH) system, based on a series of sensitivity studies using a detailed spreadsheet-based cost model. The model focuses on the first cost differences between four UFAD system alternatives and a baseline conventional OH design, and is designed to investigate tradeoffs based on nine categories of affected building elements: raised floor, HVAC system, electrical system, façade, ceiling treatment, voice and data cable, raised core, carpeting, and furniture. The first cost model was developed during the first phase of an ongoing research project whose overall objective is to develop a UFAD cost model covering both first and life-cycle cost differences between UFAD and OH buildings. In its current form, the model is intended to be used as a research tool to gain a better understanding of the tradeoffs inherent in investing in an UFAD system. Future versions of the cost model could be used to provide assistance early in the conceptual design process. This report describes the results of sensitivity studies covering a wide range of parameters using the first-cost part of the model.

Our experience in using this model for the studies included in this paper leads us to generally conclude that UFAD buildings cost more than OH buildings on a first cost basis when following the baseline assumptions of our model. These assumptions incorporate our best estimates of typical design and construction practices for UFAD and overhead systems, and were developed in collaboration with several CBE industry partners during the early stages of this project. Our baseline assumptions yield a cost premium of approximately $3.50/gross square foot (gsf) between the median UFAD building and the baseline OH building, although the HVAC system alone is slightly cheaper for the UFAD building. No single cost saving measure was sufficient to reduce the UFAD first costs enough to make up for the greater than $6/gsf premium incurred by the raised floor itself. However, the multi-parameter cost model provides an opportunity to investigate different combinations of cost-saving strategies from a variety of factors. Results for these integrated scenarios involving more aggressive strategies to maximize cost savings indicate that UFAD can be cost competitive with even the baseline OH building. Furthermore, when we changed the baseline OH assumptions to represent a higher quality overhead HVAC installation (more expensive, but still representative of typical high-end HVAC practice), the impact on cost differentials was dramatic. In this case, all UFAD buildings exhibited a significant cost savings compared to the OH building, demonstrating the important influence of the assumptions about the quality of the OH baseline building.

In this study we found that UFAD total building costs (independent of comparison to the baseline overhead building) are most sensitive to differences in material and labor markets, furniture and electrical configurations, perimeter HVAC parameters and the cost of the raised floor. Changing the parameters in any of these categories heavily influences the total cost of buildings using UFAD. However, of most concern to us in this study are those design parameters that create first cost premiums or savings for UFAD buildings with respect to the overhead convention. Generally, the areas that yielded the greatest sensitivity (cost differences >$1/gsf over the range of conditions tested) were interior zoning configurations, wall height differences, UFAD return ducting in the perimeter, airflow rate, and naturally, the quality of the baseline OH system against which all UFAD costs were compared. Those parameters found to have the least effect on cost differences between UFAD and OH buildings include workstation size, private to open office ratios (independent of zoning), floorplate size, building orientation and climate.

The process of developing and using this model leads us to believe that comparison studies done without such a tool must be scrutinized heavily for their ability to provide a true apples-to-apples comparison given the complexity of the cost tradeoffs. Comparisons of constructed systems are more daunting yet. First cost differences as described in this report, in combination with results from CBE's upcoming

UFAD life-cycle cost model (currently nearing completion), will provide a more complete basis for evaluating the cost advantages and disadvantages of UFAD buildings in comparison to OH buildings.

2 INTRODUCTION

Understanding how underfloor air distribution (UFAD) building costs deviate from those of buildings with conventional overhead (OH) systems is one of the most important issues facing the industry as UFAD becomes more commonly considered as an option for a commercial building mechanical system. However, it is a daunting effort to try to make apples-to-apples comparisons based on anecdotal or single project cost data for projects that are located in disparate areas. Our overall goal in this research effort was to create a tool that allows us to conduct analyses in a systematic way at both a first cost and life-cycle cost level. The CBE UFAD cost model in its current form is intended to be a research tool that facilitates a broad based analysis of the cost differences between UFAD and OH buildings for various design options. The model is very detailed so that we can decipher the cost drivers underlying a particular design scenario. More specifically, the objectives of our ongoing UFAD cost analysis project are defined below.

1. Develop a detailed cost model, including first and life-cycle cost (LCC) elements, which evaluates the cost differences between UFAD and traditional OH systems. The model is to be constructed so that a prototypical office building using a UFAD system for a range of design options can be compared with the same building using an OH system.
2. Use the model to conduct parametric studies of various design options and analyze the costs associated with typical alternative UFAD system designs relative to each other and to conventional OH systems.

The cost model used for this study is the CBE UFAD First Cost Model developed under funding from the U.S. General Services Administration (GSA). [Webster et al. 2005]. Previous reports described initial groundwork that formed the foundation for this project [Hurley et al. 2002] and the development of the first cost model [Webster et. al. 2003]. The original project statement of work described the overall methodology for this project, including the development and sensitivity analysis of a life-cycle cost component (still under development as of September 2006) and the integration of it with the first cost model [Webster and Bauman 2002]. This report is an interim report that encompasses work through Task 3.1 of the project statement of work.

In this report we document the results of our analysis of UFAD system first costs using the CBE UFAD first cost model. During our analysis, we used the model to investigate the sensitivity of UFAD system first costs to building geometry and interior configurations, HVAC alternatives, and an integrated (multi-parameter) scenario.

3 DESCRIPTION OF FIRST COST MODEL

3.1 MODEL COMPONENTS

We designed the model in a modular format composed of various components where each has a specific function. This modular structure facilitates changes and improves development workflow.

Figure 1 is a diagram where we show the overall structure of the first cost model.

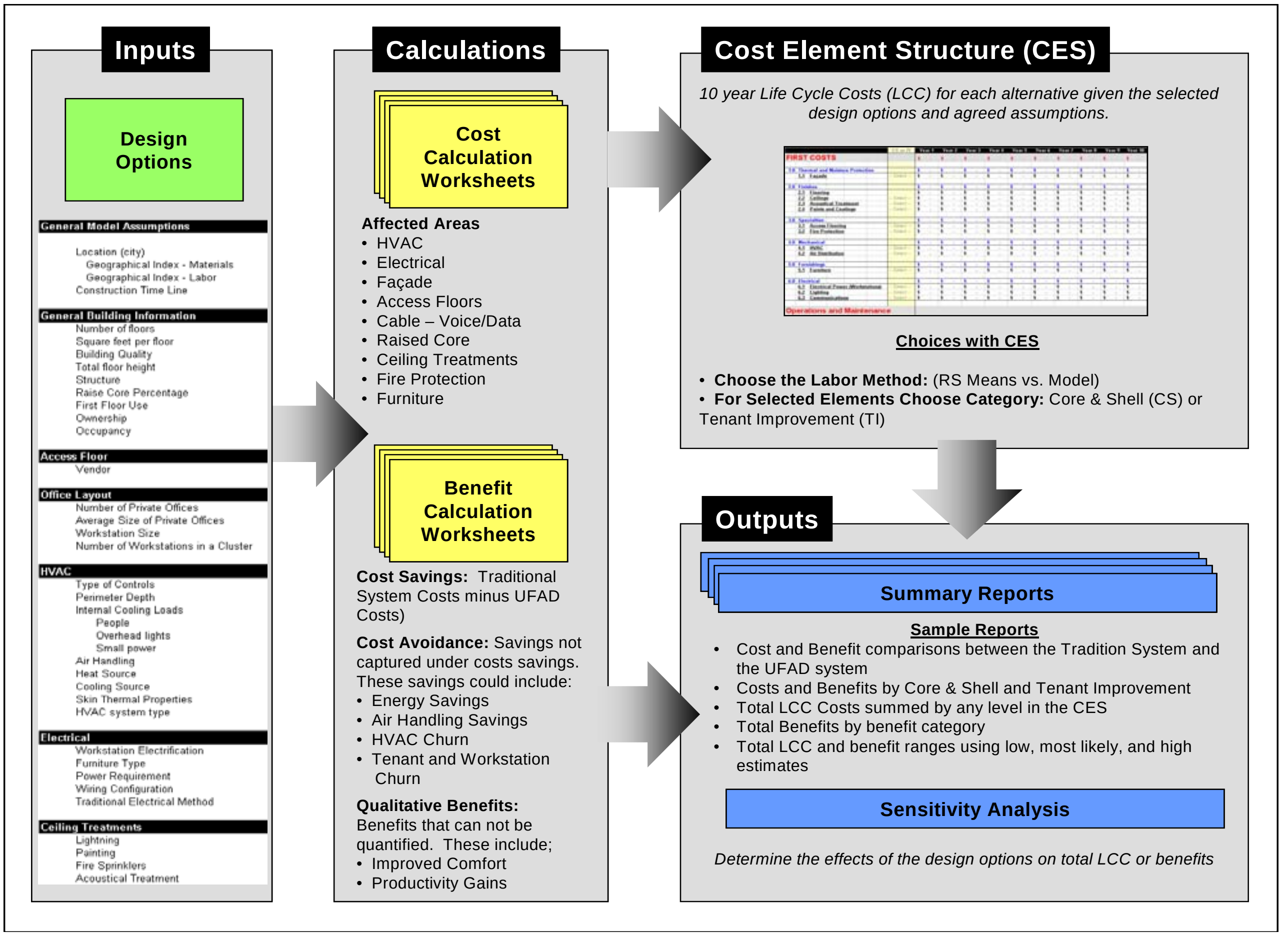


Figure 1. Cost Model Structure

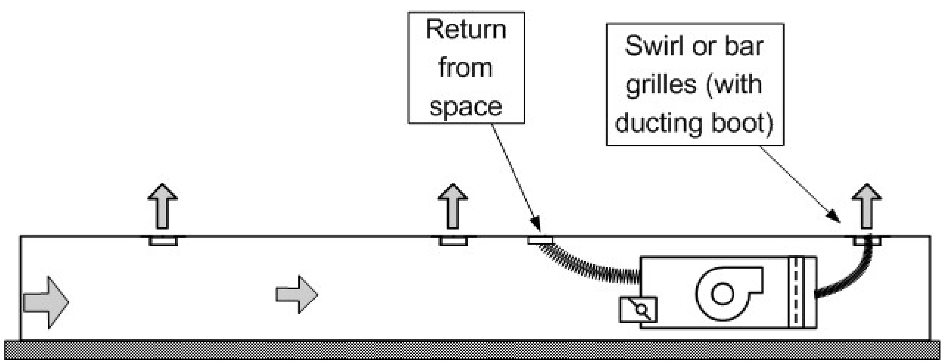
The model is embodied in an Excel workbook that includes the following components: Design Option Input Worksheet, Cost Calculation Worksheets, Benefit Calculation Worksheets, Cost Element Structure (CES), and Summary Reports. Each of these has been discussed in detail in our reference document [Webster et al. 2003]. For each affected element (see below) we have crafted detailed models derived from input from specialists (contractors, engineers, builders, and product manufacturers) experienced in the trades included in a given element. We used estimating methods and data supplied by these practitioners as opposed to generic estimates provided by resources such as RS Means[1]. We created over sixty design option elements that can be user selected, not counting labor rates. We researched and constructed a very detailed labor rate model based on San Francisco rates with indexing to other US locations. The model assumptions have been documented internally concurrently with the development of the first cost model and are still in process with the ongoing development of the life-cycle-cost section of the model [Webster et al. In press]. Generally for this project we have assumed a multistory office building with a floorplate size, length to width ratio and many other options specified by the user. The full list of baseline assumptions is included in a later section (see complete report.)

[1] In some cases where the detail we sought was unnecessary or not available, we relied on RS Means data.

3.1.1 ALTERNATIVES

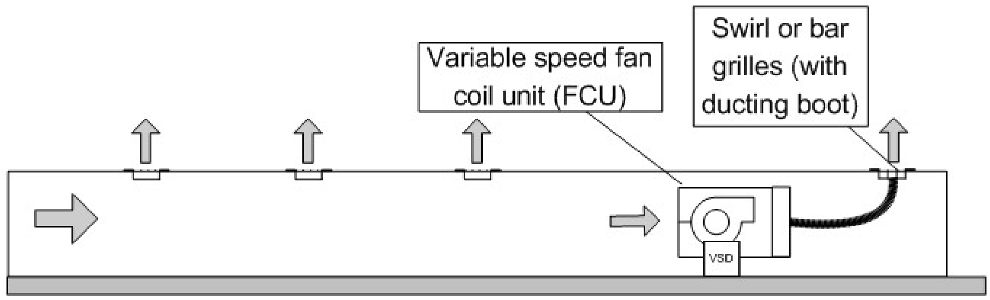
We define alternatives to be the basic system designs to be compared to one another. One traditional OH HVAC system and four alternative HVAC systems are currently included in the model. These alternative HVAC designs are shown schematically and described briefly below.

1. Overhead (OH) - This is the baseline for comparison to all UFAD systems. It is a traditional overhead variable-air-volume (VAV) air distribution system using single-duct VAV boxes in the interior, hot water reheat boxes in the perimeter and perforated diffusers throughout. For climates where heating requirements result in reheat exceeding ASHRAE allowances, fan powered boxes (FPB) are specified. This is intended to be a basic, low cost design and represents one end of the spectrum of possible OH systems. The opposite end (provided via the options available for OH) is represented by the a higher quality OH VAV system that uses parallel fan powered boxes in the perimeter as well as slot diffusers throughout. Many systems in real buildings will fall in between these two extremes.
2. UFAD A, All CAV – This system has been included to provide continuity with older practices; few of these systems are being built today. This alternative has a constant air volume (CAV) system in the interior with air provided by separate AHUs or fixed mains dampers. In some cases pressure control dampers may be used to maintain a constant plenum pressure but this variation is not estimated by the model. We assume the interior to be one large zone with temperature control provided by the AHU. The perimeter is served by constant volume series fan powered boxes with hot water reheat coils. Because it is a constant volume unit, mixing dampers at the entrance to the FPB that are connected to the plenum and the room are used to provide temperature control. We assume interior diffusers are swirl (Price units are used in the model) and perimeter are linear bar grilles supplied by Titus (as are the FPBs).



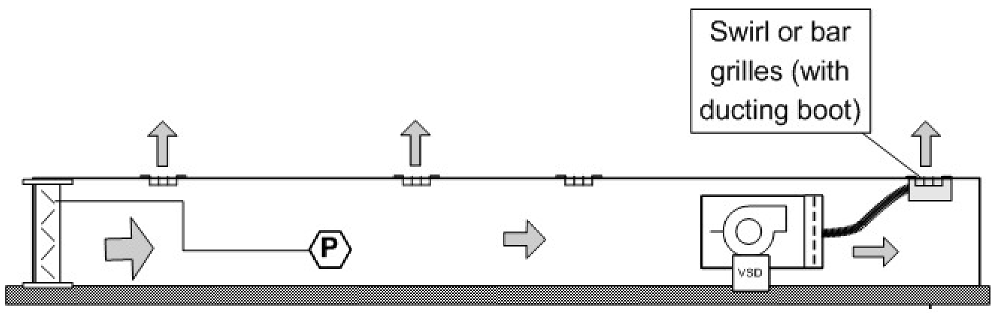
UFAD-A: All CAV, CAV interior and perimeter with series FPB

3. UFAD B, CAV/VAV - This system is similar to UFAD A except the perimeter is served by VAV fan coil units (FCU) with variable speed drives. In this case we also assume Price swirl diffusers in the interior and Greenheck FCUs for both cooling and heating in the perimeter. As shown in the schematic below, plenum air is provided to the FCU (thus incurring some additional reheat during heating mode) but the discharge is connected to the bar grilles by flexible ducting. A hot water reheat coil provides heating. In this system plenum pressure may vary due to the varying demands of perimeter system.



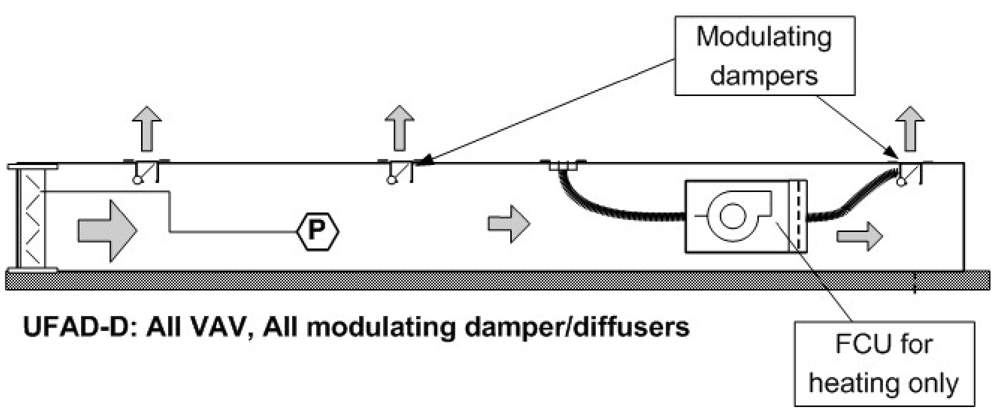
UFAD-B: CAV/VAV, interior CAV, perimeter VAV with VSD/FCU

4. UFAD C, All VAV – This system, in its generic form shown here, represents one of the most common UFAD systems types being built today. We assume the perimeter uses the same system as UFAD B, but the interior, while using Price swirl diffusers, is equipped with modulating dampers to control plenum pressure to provide VAV control of interior zones.



UFAD-C: All VAV: interior modulating dampers, swirl diffusers

5. UFAD D, All VAV – This all VAV systems represents York International's Flexsys offering. In this case all diffusers, interior and perimeter, are modulating variable area boxes that are controlled in groups. Plenum pressure is typically controlled to a constant value by interior modulating dampers (although some systems reset this pressure based on demand). Although a FCU unit is included in the perimeter, it is only used for heating mode and is therefore a smaller capacity than those used in UFAD B and C.



UFAD-D: All VAV, All modulating damper/diffusers

3.1.2 AFFECTED ELEMENTS

We developed the model around the concept of “affected elements.” Affected elements are the key building elements that may change when a UFAD system is used. The affected elements are:

- Raised Floor
- HVAC Systems
- Electrical Systems
- Façade
- Cable – Voice/Data
- Raised Core
- Ceiling Treatment
- Carpeting
- Furniture

The affected elements list was developed through extensive interviews with commercial building practitioners. All other building elements are assumed to be unaffected. In other words, the first costs for these other unaffected elements are assumed to be equivalent for both UFAD and OH buildings.

In many of the studies included in this report, we have grouped some of these elements together to form five summary categories, each of which includes affected elements that seem to logically fit together:

- Core, Carpet, Raised Floor – includes the premium for the raised floor and the raised core.
- Façade, Ceiling Treatment – includes lighting and fire proofing
- HVAC – includes perimeter and interior terminals, ducts and diffusers as well as underfloor dampers and dividers and central system differences.
- Electrical, V&D – includes electrical, voice and data cabling
- Workstations – includes furniture costs

3.1.3 INCREMENTAL VS. TOTAL COSTS

Incremental costs represent the cost differential between a UFAD and OH affected element. A total cost analysis would use the total cost of the entire building component for each alternative to determine the difference. As an example let’s consider the façade affected element. The fundamental difference between UFAD and OH alternatives is due to the potential reduction in floor-to-floor height of the building. This could result in reduced façade costs for the UFAD alternative. In an *incremental analysis*, we assume that the cost difference is only a function of one element of the wall, the spandrels and their associated costs; the cost of this sub-element we can estimate without having to estimate the entire wall. (i.e., to calculate this difference, we multiply the reduction in floor-to-floor height by the spandrel costs, not the unit cost of the entire wall). In a *total cost analysis*, the total façade costs, including windows, finishing, masonry, etc., would be included in the difference calculation.

In the model, where appropriate, we use incremental costs as opposed to the total cost for the affected elements. In some cases, and only where necessary, (e.g., HVAC systems) a more comprehensive cost of an entire affected element may be estimated to illustrate the difference between UFAD and OH in greater detail. When overall costs of a system are discussed as opposed to differentials between UFAD and OH, the “total affected costs” represent the sum of all costs for the affected elements only. These values are for relative comparison purposes only and should not be considered a statement of the actual cost of the building, or building element.

3.2 BASELINE DESIGN INPUTS

Unless stated otherwise in the individual studies discussed in this report, all studies were formulated from the same baseline list of assumptions and design options. All analyses were based on climate and materials and labor rates for San Francisco. The baseline building is a 20,000 square foot multistory building with a length to width ratio of 1.5. Underfloor air distribution systems and overhead systems are assumed to use the same design airflow (except where noted) but have somewhat different zoning configurations. The gross floor area contains approximately 21% private offices in both the interior and perimeter zones and the perimeter zone is designated as the space within 15 feet of the building perimeter. Baseline design options are meant to follow popular design convention. A full list of the baseline design options is located later in this report (see complete report.)

There are a few instances in this paper where a particular sensitivity study (set of model results) does not include an instance of the original baseline for the sake of keeping the comparison fair within the study itself. For example, in the private offices studies, we remove the 1500 cfm limit on interior OH VAV boxes in order to allow for a more fair comparison in the interior zone between UFAD and OH. We have noted in the studies and the charts where the original baseline was used as the basis for comparison within the study itself.

4 ANALYSIS METHODS

We conducted parametric sensitivity studies for three general categories: Building geometry and interiors, HVAC, and an integrated scenario. For each study, we altered variables in each simulation run according to our best understanding of common design options and typical ranges of variability. For presenting the results, we distilled the data into the five summary categories mentioned above. For those runs where variations in relative cost only occurred in one of the five categories above, we provide a more detailed affected element breakdown.

We show results in two basic formats: total affected costs and cost differential from overhead (OH). Total affected costs show the relative magnitudes of overall costs for each affected element or category (i.e. the total incremental costs as described in section 3.1.3). We use this method primarily in cases where we want to show how the OH system element or total cost changes relative to other options or system types.

Cost differential is simply the cost of UFAD minus the cost of OH. When UFAD costs are greater than OH we designate it a premium for implementing UFAD; when they are less than OH we designate it a savings. Note also that when cost differentials are shown for a given affected element or category (perhaps the only one affected), the premium or savings shown for this single factor does not represent the overall impact on building costs, it is the sum of all these factors that determines the building *total differential*. We should also point out that the *relative* magnitude of a given affected element or category (i.e., as a percentage of the total cost) varies significantly depending on the element. Thus for a small cost component the potential for influencing the total differential may be small.

Table 1 shows the breakdown of total affected costs and their relative proportions for each affected element of the baseline OH specification, one of the UFAD systems (UFAD C), as well as the difference in cost between these two buildings in the final, “differential,” column. Note that for the baseline total, there is a total differential of $3.50/gsf; i.e., a cost premium for UFAD over OH. Table 1 shows that the largest premium expense for UFAD is the raised floor itself, though furnishings and HVAC are actually less expensive for UFAD. This cost savings in UFAD for furnishings and HVAC (including ductwork savings) is not enough to offset the $6.52/gsf premium for the raised floor. However, this differential depends to a large extent on the particular assumptions we made for the baseline configurations.

Table 1. Baseline OH vs. UFAD C Cost Breakdown

	OH		UFAD C		Differential (UFAD – OH)
	Category Cost	Percent of Total	Category Cost	Percent of Total	
Total	**$36.69**	**--**	**$40.19**	**--**	**$3.50**
Raised Core	$0.00	0.0%	$0.44	1.1%	$0.44
Carpeting	$2.94	8.0%	$2.86	7.1%	-$0.08
Access Flooring	$0.00	0.0%	$6.52	16.2%	$6.52
Façade	$0.00	0.0%	-$0.01	0.0%	-$0.01
Ceilings treatments	$6.59	18.0%	$6.59	16.4%	$0.00
HVAC	$10.12	27.6%	$9.70	24.1%	-$0.42
Electrical	$2.26	6.2%	$4.00	9.9%	$1.73
V&D	$1.26	3.4%	$0.63	1.6%	-$0.63
Workstations	$13.51	36.8%	$9.45	23.5%	-$4.06

The breakdown in Table 1 points out how important it is to be making appropriate comparisons and why there are problems with anecdotal studies where the details of the assumptions are not known or may not be held constant in the comparison. The access flooring premium for UFAD could be offset easily in the combination of the HVAC, ceiling, and furniture and electrical elements that represent the major cost items. This is particularly true for HVAC where the cost can vary widely based on the details of its configuration, as shown below in the OH System Quality study.

Furthermore, for the sensitivity studies that we describe in this report, it is the *change* in the total differential (i.e., the sensitivity) as the study parameter changes that are important to focus on in these analyses. In this light, the sensitivity studies allow us to determine the change in a unit cost difference over a given range of design input parameters that we can apply to the total building cost differential to evaluate the impact of changes in a particular parameter. We explain these issues in more detail at the beginning of the Results and Discussion section.

4.1 MODELING ISSUES, IMPACT OF AIRFLOW CALCULATIONS

In the model we calculate the UFAD airflow in the perimeter based on load calculations and an assumed/estimated space stratification. The load calculations account to some extent for heat transfer to the supply plenum by using a factor of 0.75 W/gsf through the floor. This amounts to about 17% of the total internal gains. Recent work at CBE [Bauman et al., 2006] suggests that this is close to expected heat transfer to the plenum due to radiation from the ceiling, but it does not represent the total heat transfer from the space to the plenum in a multi-story building. The CBE results indicate that another ~15-20% of the space gains are transferred to the plenum via conduction through the slab in the return plenum. Thus the model will calculate conservative airflows (i.e., on the high side). In addition, for interior loads we assume a user specified airflow rate per square foot, except in conference rooms. For OH systems we calculate both interior and perimeter loads using standard loads calculations. Both of these effects on UFAD airflow calculations are mitigated in the studies reported here due to the fact that we conducted most of our analyses with airflow for UFAD equal to that of OH for both interior and perimeter zones. The CBE study indicates that this is in fact close to how real systems operate unless steps are taken to maximize stratification using very low throw diffusers, which is not commonly done.

4.2 STUDY CATEGORIES

4.2.1 BUILDING GEOMETRY AND INTERIORS

The purpose of the building geometry parametric analysis was to develop an understanding of the sensitivity of whole-building decisions concerning the relative cost of the UFAD alternatives. Studies in this category included whole building geometry options, furniture and interior finish elements, as well as electrical and thermal envelope elements.

4.2.2 HVAC

We conducted these studies to understand the sensitivity in HVAC costs due to various HVAC design options. Within this category, we focused on: envelope loads, interior loads, zoning, and other design configurations of UFAD systems.

4.2.3 INTEGRATED SCENARIO

Finally, we ran an integrated scenario to study the combined effects of multiple building elements, including building structure type, ceiling treatment, wall height savings, furniture type, and floor installation labor rate in an attempt to determine if we could lower the UFAD premium with aggressive design and construction practices.

5 RESULTS AND DISCUSSION

(For a complete presentation of results and discussion, please see the full report.)

6 SUMMARY AND CONCLUSIONS

6.1 BUILDING GEOMETRY AND INTERIORS

Figure 2 and Figure 3 show summaries of two groups of building geometry and interiors studies in an effort to obtain a "big picture" view of the comparative sensitivity of the factors investigated in this report. The graphs show the range of affected cost differentials for each set of runs for baseline conditions and up to two additional cases, as described previously in this report. Table 2 is a summary of the parameters used in the various studies when plotting the baseline and two study cases in the summary graphs. For studies involving more than three sets of parameters, we have selected the maximum and minimum, along with the baseline, to show the full range of cost variations. In the figures, the vertical lines with greater ranges indicate a larger sensitivity to the factor studied across the range of inputs explored. The dark data points represent the baseline for that study. Note that the baseline results for each UFAD system are the same for all studies where this baseline was not expressly altered (private office and zoning studies have a different baseline).

From these charts we can see that Floorplate Size, Wall Thermal Quality, Electrical, Floor to Floor Height (Return Air Plenum Height) and the Integrated Study exhibited the most sensitivity regarding the difference between OH and UFAD costs whereas Length to Width Ratio, Raised Core Area and Orientation had the least effect on cost sensitivity. This chart also shows that the cost premium for UFAD systems B, C, D is in the range of $2-4/gsf while UFAD A is nearly $6/gsf. Also, for most of the studies, the variation across the range studied is about $1.5-$2/gsf. For the integrated study the range of variation is almost $7/gsf and extends from an overall cost savings of about $2-$3/gsf for some options. Another general trend occurs in this graph as well. UFAD A is generally the most costly of all systems, and OH is generally the least. UFAD B is generally the least costly UFAD system and UFAD C and UFAD D are generally comparable in cost.

Generally, though many of the studies we have discussed in this paper focus on fluctuations in the Mechanical/HVAC cost element, this element is much less significant when compared to the

Core/Carpet/Access Flooring cost which always adds a significant premium over the baseline OH system cost, or the workstations cost, which always adds a significant savings compared to overhead.

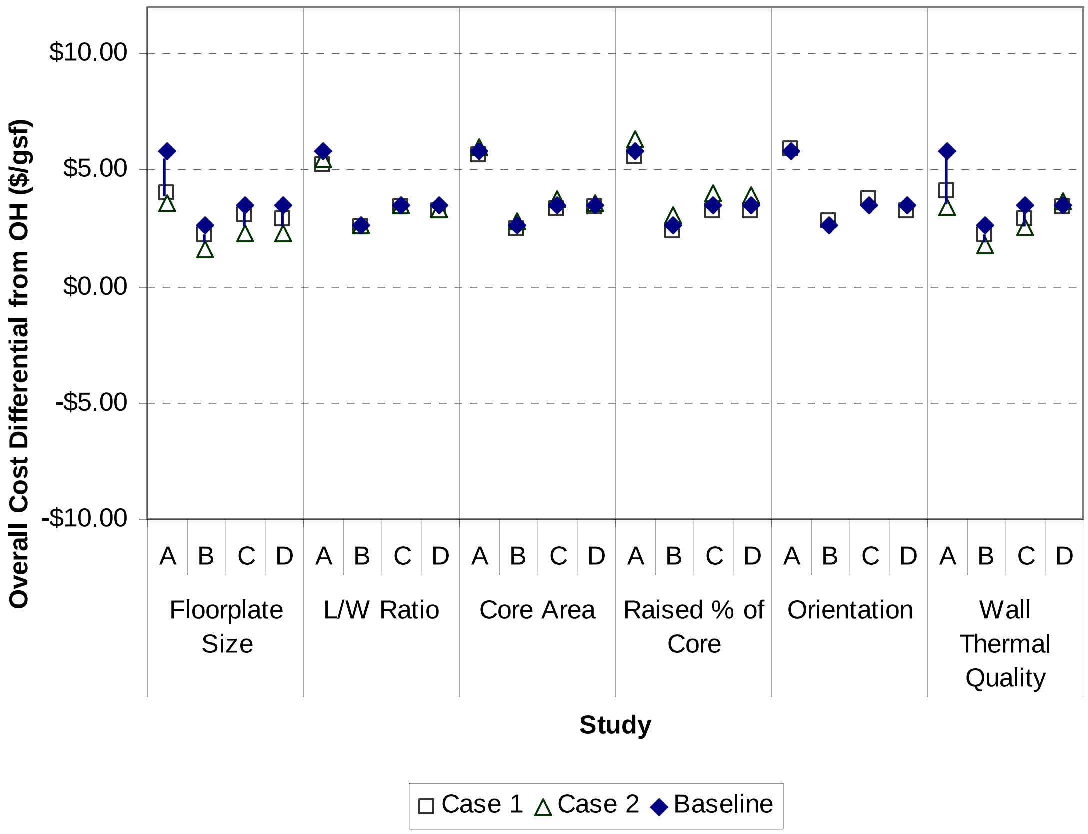


Figure 2. Building Geometry and Interiors, Group 1: Differential Sensitivity Summary

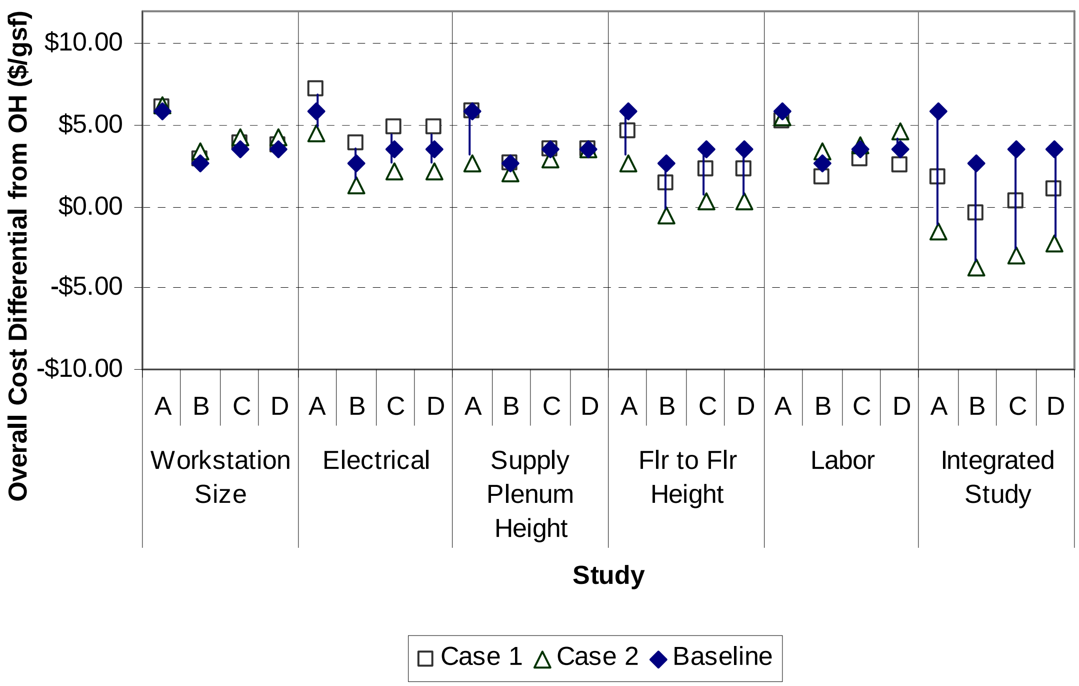


Figure 3. Building Geometry and Interiors, Group 2: Differential Sensitivity Summary

Table 2. Building Geometry and Interiors: Summary of study parameters

Study	Baseline	Case 1	Case 2
Floorplate Size	20,000 sf	35,000 sf	50,000 sf
L/W Ratio	1:(2/3)	1:(1/2)	1:1
Core Area	10%	5%	15%
Raised % of Core	50%	25%	100%
Orientation	E/W	N/S	
Wall Thermal Quality	Good	Better	Best
Workstation Size	8'x8'	9'x9'	10'x10'
Electrical	OH Powerpole	C / P	M / NP RF All
Supply Plenum Height	14"	12"	18"
Floor-to-Floor Height	Steel / Hung	Concrete / Exposed	UFAD Concrete / OH Steel
Labor	San Francisco	New York City	Charlotte
Integrated Study	Standard Baseline	Scenario 2	Scenario 4

6.2 HVAC

Figure 4 shows a summary of results from the first group of HVAC studies focused on private offices and zoning. The values shown are those corresponding to overall cost per gross square foot of each system (not only HVAC costs) based on the parameters listed in Table 3. Based on these studies, the following key conclusions can be made:

- The percent of private office (**Error! Reference source not found.**) has little effect except for private office dominated buildings when equal zoning between OH and UFAD is imposed. This results in a ~$3/gsf savings for UFAD D, and ~$1.5/gsf for UFAD C for a private-office dominated building (67% private offices).
- The impact of number of interior zones (for UFAD C) is large only above 8 zones (~$3/gsf increase when UFAD interior zones are increased from 1 to 16).
- The number of private offices per zone has little impact on cost differential except in the unlikely event of only one private office per zone.

Figure 5 presents a summary of results from the second group of HVAC studies that focus on overall parameters aside from private offices and zoning. The parameters used to generate these studies are also listed in Table 3. For the studies shown, overall cost differentials are most sensitive for the airflow and OH system quality studies. The following key conclusions can be made:

- Differences in climate have a relatively small effect on the order of $2/gsf considering only the impact of thermal loads (not labor and material rates) for these locations.
- It would take relatively large reductions in airflow (i.e., ~30%) for UFAD to achieve cost savings on the order of $2/gsf.
- Cost differences between OH and UFAD have the greatest sensitivity to OH system quality. UFAD savings in the range of $6-$9/gsf are realized if premium OH systems are the basis for comparison. These results indicate that the quality of OH systems can have a profound effect on the cost comparison and that choosing the OH baseline can be crucial to understanding the cost differences between UFAD and OH. Our findings indicate that UFAD is very cost competitive when compared to higher quality OH systems.
- Adding return air ducting to perimeter systems in UFAD B and C results in added costs of about $2/gsf. This added first cost should be reviewed on a life-cycle basis to determine if it is cost effective.

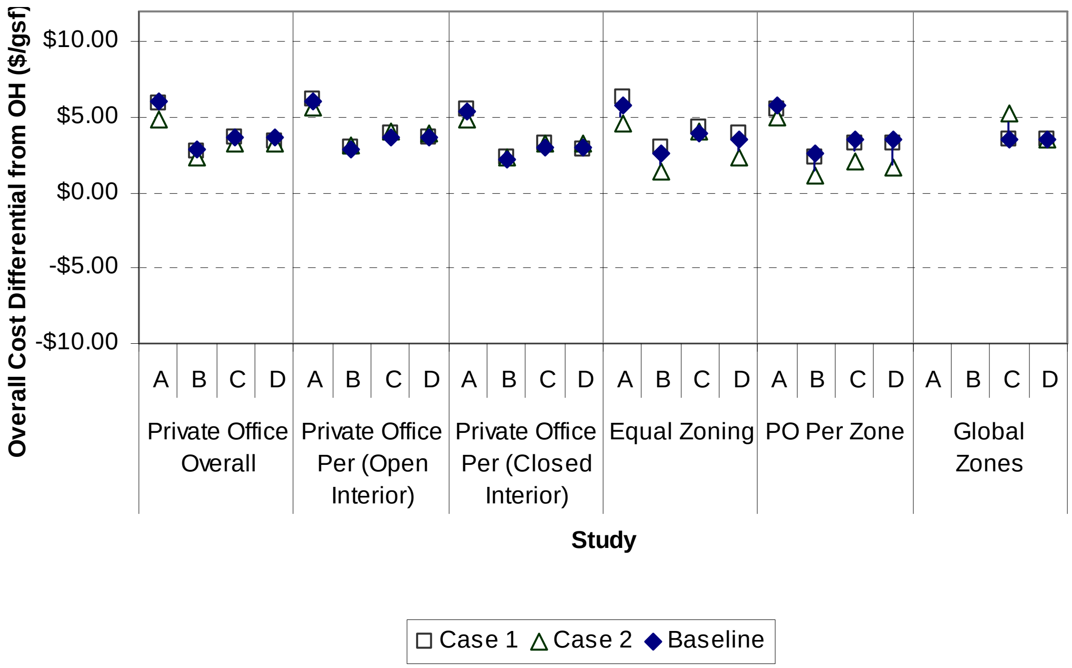


Figure 4. HVAC - Private Office and Zoning: Differential Sensitivity Summary

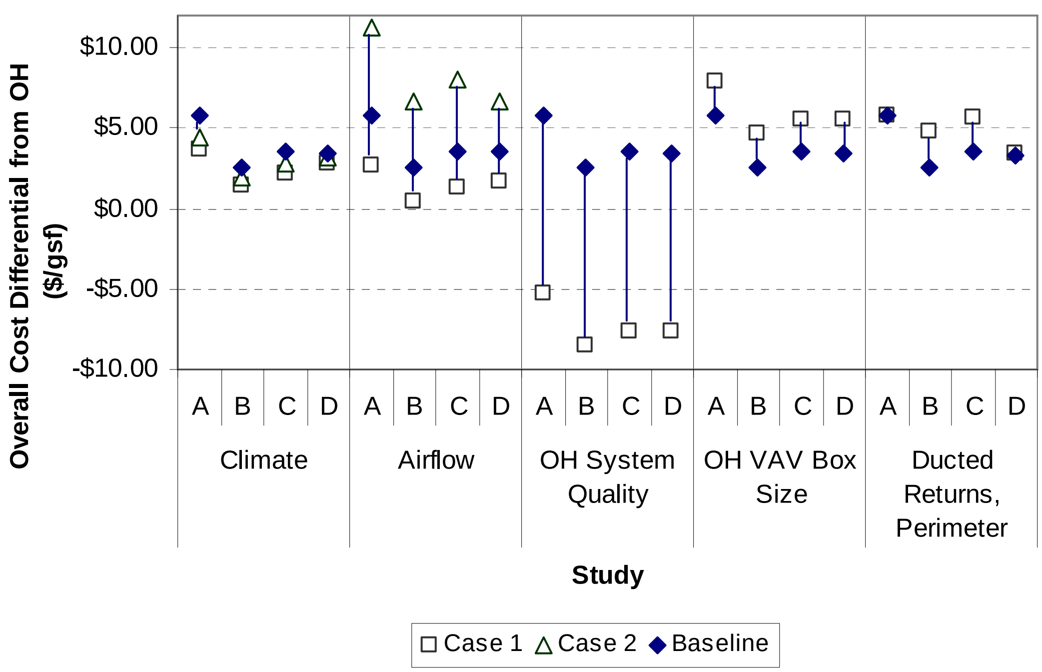


Figure 5. HVAC - Overall Factors: Differential Sensitivity Summary

Table 3. HVAC: Summary of study parameters

Study	Baseline	Case 1	Case 2
Private Office Overall	21%	43%	65%
Private Office Per (Open Interior)	21%	43%	65%
Private Office Per (Closed Interior)	21%	43%	65%
Equal Zoning	21%	43%	65%
PO Per Zone	5	3	1
Interior Zones for UFAD C	1	4	16
Climate	San Francisco	Baltimore	Phoenix
Airflow	0%	-30%	30%
OH System Quality	Good	Better	N/A
OH VAV Box Size	Limited to 1500 cfm	Largest Available	N/A
Ducted Returns in Perimeter UFAD	No Ducted Returns	Ducted Returns	N/A

6.3 GENERAL CONCLUSIONS

Besides the detailed findings discussed above and amplified in the results section, several overall conclusions and observations derived from conducting this study can be made:

- While conducting these studies we learned that it can be a somewhat daunting task to achieve a true apples-to-apples comparison between OH and UFAD systems. Despite having a comprehensive model to conduct systematic studies, it is still sometimes difficult to make all things equal. In addition, some issues are not easily understood as to their overall significance. For example, it is not clear what the impact is of differences in zoning. When we interview design professionals we find wide differences in opinion and detailed comfort studies have not been done to help answer this question. Furthermore, we are only beginning to understand how the comfort of stratified systems compares to mixed systems.
- Models such as this one are necessary to fully capture the countervailing impacts as design options are changed. This can lead to some non-intuitive results which demonstrate the power of using models for these types of comparisons. One clear example of this is represented by the private office studies where the opposing changes in furniture and electrical costs essentially cancel the effect of moving from an open plan to a private office dominated building.
- In our labor and materials rates study we showed that the total cost for these systems, both UFAD and OH, vary dramatically depending on location. However, the UFAD premium was reduced by ~$1.5-$2/gsf for the most expensive locations compared to least expensive.
- Of the sixteen studies that we conducted only a handful resulted in impacts of more than $3/gsf that materially altered the nominal $3.5/gsf UFAD premium for our baseline configuration. When we varied the design options over reasonable practical ranges the effect on OH to UFAD differential was mostly in the range of $1-$2/gsf. Only when we combined options to maximize UFAD savings did we produce overall savings for UFAD on the order of $2-$3/gsf.

  However, the largest factor by far that influences this differential is the assumptions made about the quality of the OH system used for comparison. The difference between a "plain vanilla" VAV system and a top quality system resulted in the differential change from a $3.5/gsf UFAD premium to a ~$6-$8/gsf UFAD savings over OH.

- First cost differences as described in this report, in combination with results from CBE's upcoming UFAD life-cycle cost model (currently nearing completion), will provide a more complete basis for evaluating the cost advantages and disadvantages of UFAD buildings in comparison to OH buildings.

7 ACKNOWLEDGMENTS

7.1 PROJECT CONTRIBUTORS

Funding for this work was provided by the U.S. General Services Administration (GSA) Public Buildings Service Research Program under Contract Number GS-00P-02-CYC-0071. We would like to express our sincere appreciation to Kevin Kampschroer of GSA for his timely and considerate support for this project. We wish to thank all our CBE partners for their invaluable support and assistance in providing guidance during the early stages of our work on the economic analysis of UFAD systems. In particular, this project has greatly benefited from the extensive knowledge and expertise of the following individuals: Steve Taylor, Taylor Engineering; Phil Williams and Eric Horn, Webcor Builders; David Diamond, SOM; Mike Critchfield, CMI; and Michael Albright and John Brown, Rosendin Electric. We would also like to acknowledge David Lehrer, CBE Director of Partner Relations for his support and excellent facilitation of our research advisory committee meeting. Also, we appreciate the valuable assistance that Bill Reynolds of Tate Access Floors has provided by offering the use of Tate's UFAD costing tool.

This project would not have been possible without the large and dedicated research team that worked on this project. We express our appreciation to the following former graduate student researchers for their invaluable contributions to this project: Bonnie Elgamil, Jason Wallis, Haibin Lin, and Nash Hurley. In particular we would like to mention Ronaldo Pinto for his outstanding effort in creating the electrical and HVAC models as well as many of the summary reports.

7.2 CENTER FOR THE BUILT ENVIRONMENT

The Center for the Built Environment (CBE) was established in May 1997 at the University of California, Berkeley, to provide timely unbiased information on promising new building technologies and design strategies. The Center's work is supported by the National Science Foundation and CBE's Industry Partners, a consortium of corporations and organizations committed to improving the design and operation of commercial buildings.

CBE's current Industry Partners include:

Armstrong World Industries
Arup*
California Department of General Services
California Energy Commission
Charles M. Salter Associates Inc.
Flack + Kurtz Inc.
HOK
Pacific Gas & Electric Company
Price Industries
RTKL Associates Inc.
Skidmore, Owings & Merrill, LLP
Stantec
Steelcase, Inc.
Syska Hennessy Group
Tate Access Floors, Inc.*
Taylor Team: CTG Energetics, Guttmann & Blaevoet, Southland Industries, Swinerton Builders, Taylor Engineering
Trane
U.S. Department of Energy*
U.S. General Services Administration*
Webcor Builders*
York International Corporation

* founding partner

Center for the Built Environment (CBE)
A National Science Foundation Industry/University Cooperative Research Center
390 Wurster Hall #1839, Berkeley, CA 94720-1839
tel: 510.642.4950 fax: 510.643.5571
cbe@berkeley.edu www.cbe.berkeley.edu

8 REFERENCES

Bauman, F., H. Jin, and T. Webster. 2006. "Heat Transfer Pathways in Underfloor Air Distribution (UFAD) Systems." *ASHRAE Transactions*, Vol. 112, Part 2.

Hurley, N., F. Bauman, and T. Webster. 2002. "Cost Considerations of Underfloor Air Distribution Systems." Center for the Built Environment, University of California, Berkeley, October.

Webster, T., and F. Bauman. 2002. "Underfloor Air Distribution (UFAD) Cost Study: Model Completion and Cost Analyses." Statement of Work submitted to U.S, General Services Administration, Center for the Built Environment, University of California, Berkeley, September.

Webster, T., B. Elgamil, F. Bauman, and J. Wallis. 2003. "Underfloor Air Distribution (UFAD) Cost Study: Phase I – Model Development." Submitted to General Services Administration, Center for the Built Environment, University of California, Berkeley, February.

Webster, T., R. Pinto, and B. Elgamil. 2005. "CBE UFAD First-Cost Analysis Model." Center for the Built Environment, University of California, Berkeley.

Webster, T., R. Pinto, B. Elgamil, C. Benedek, F. Bauman, J. Wallis and H. Lin. In press. "CBE UFAD Cost Analysis Model: UFAD Cost Model, Issues and Assumptions." Center for the Built Environment, University of California, Berkeley.

RS Means. 2004. "Building Construction Cost Data." Construction Publishers and Consultants, Kingston.