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

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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.

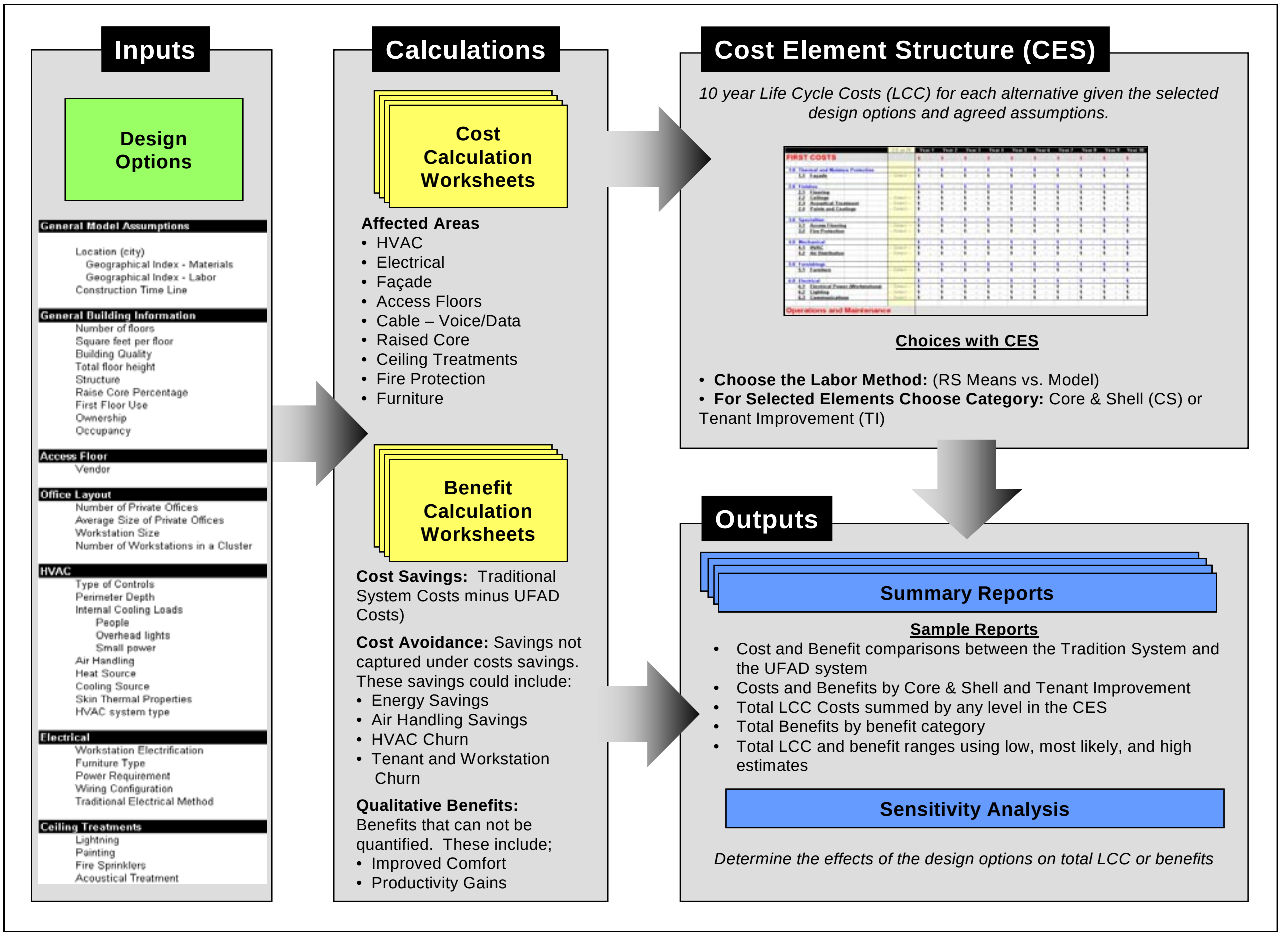


Figure 1. Cost Model Structure

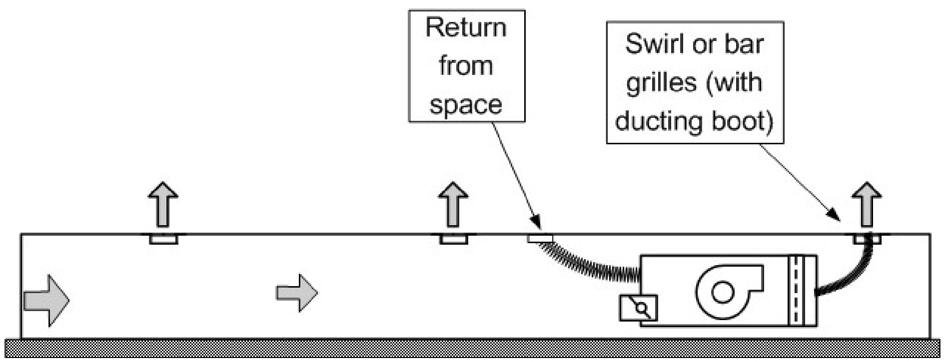
The model is embodied in an Excel workbook that includes the following components: Design Option Input Worksheet, Cost Calculation Worksheets, Benefit Calculation Worksheets, Cost Element Structure (CES), and Summary Reports. Each of these has been discussed in detail in our reference document [Webster 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 Appendix A: Baseline Design Inputs.

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

3.1.1 ALTERNATIVES

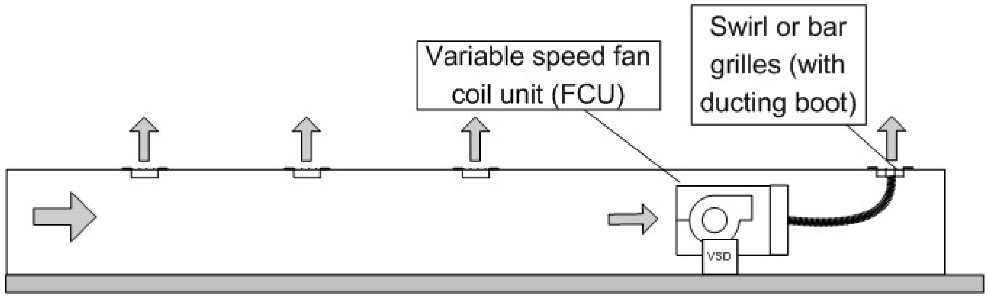
We define alternatives to be the basic system designs to be compared to one another. One traditional OH HVAC system and four alternative HVAC systems are currently included in the model. These alternative HVAC designs are shown schematically and described briefly below.

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).



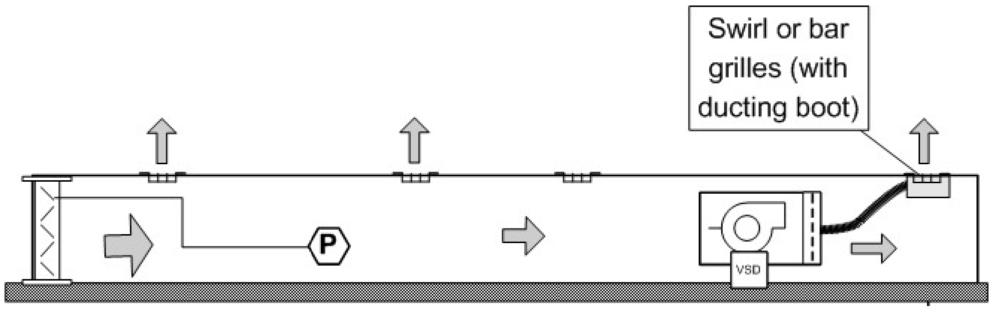
UFAD-A: All CAV, CAV interior and perimeter with series FPB

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.



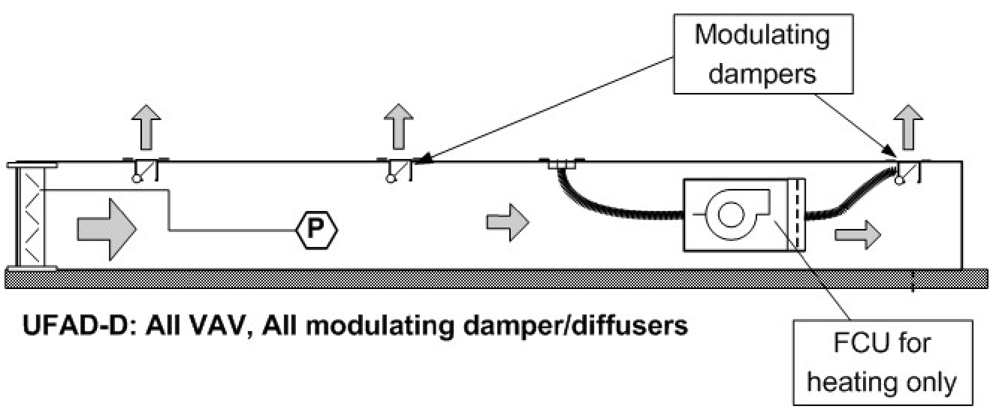
UFAD-B: CAV/VAV, interior CAV, perimeter VAV with VSD/FCU

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 in Appendix A: Baseline Design Inputs.

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

5.1 BUILDING GEOMETRY AND INTERIORS

5.1.1 Gross Floor Plate Size

In this study, we tested three different gross floor plate sizes of 20,000 sf (baseline), 35,000 sf, and 50,000 sf. In order to keep our results consistent, we changed the number of private offices to keep the percentage of floor plate being used as private office and conference rooms consistent for all three scenarios in both the interior and perimeter spaces. This may or may not be a realistic assumption but we studied the effect of changing the ratios of private offices in the zoning studies covered in Sections 5.2.2 and 5.2.3 below and found very little effect due to percentage of private offices. We also assumed a perimeter zone within 15 feet of the outside wall. As floorplate size gets larger, the perimeter area becomes a smaller portion of the building relative to the interior, as shown in Table 2. In this study, all other envelope sizes and properties remained constant.

Figure 2 shows the trend of total affected costs for each system design as floorplate increases. As noted above, these total affected cost figures are not actual costs since only the affected elements are included in the costs (the total cost was not estimated). Here we show total affected costs as opposed to total differential to emphasize how both OH and UFAD costs change when we increase the floor area. Table 3 lists the category cost differentials for each of the three floorplate sizes studied. In this analysis, as in most, we note that UFAD is more expensive than OH as it is difficult to overcome to UFAD first cost premium due to the raised floor. The $3.50 differential between OH and UFAD C shown in Table 1 may be seen in the 20,000 sf (baseline) scenario in Figure 3.

These results show a decrease in cost of each system alternative with increased floorplate, though the UFAD systems generally decrease in cost more significantly than the OH system. It is clear also, that the sensitivity in differential as floorplate increases is essentially equivalent for all cases except for UFAD A, which is more sensitive as shown by the larger change in differential over the range of floorplate sizes tested.

Table 2. Building Size: Perimeter / Interior Ratio

Floorplate Size (sf)	Perimeter / Interior Ratio	Perimeter / Total Floorplate Ratio
20,000	0.63	0.39
35,000	0.43	0.30
50,000	0.34	0.26

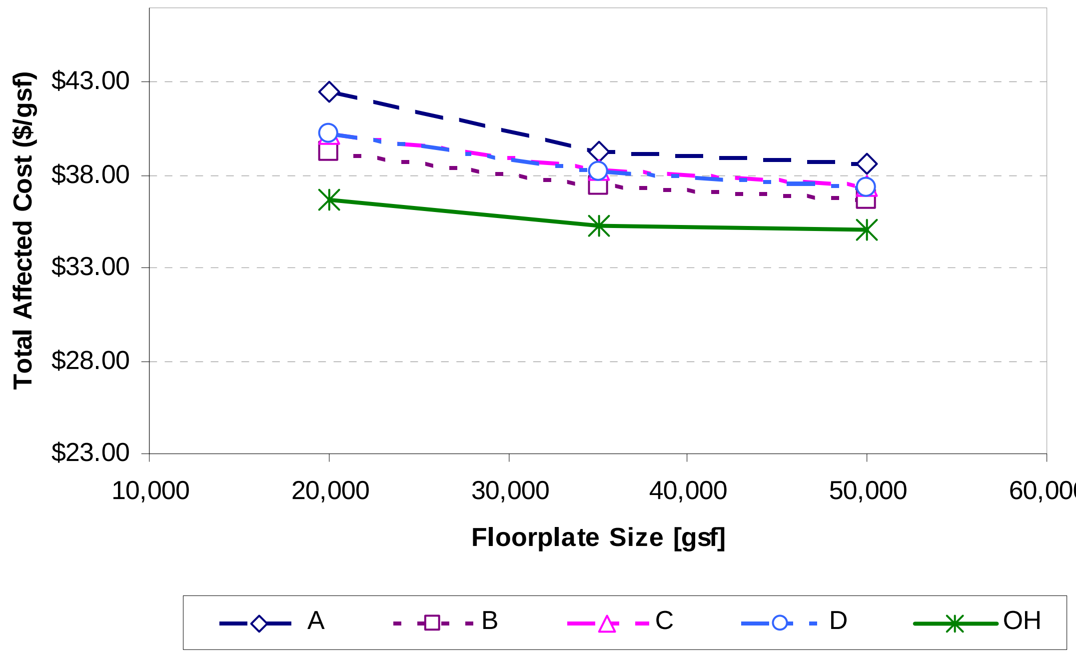


Figure 2. Floorplate Size: Total Cost Trend (Note that A thru D refers to UFAD alternatives A through D)

Table 3. Floorplate Size: Total Cost Differentials from OH ($/gsf)

UFAD System	A	B	C	D
20,000 gsf	$5.82	$2.60	$3.50	$3.49
35,000 gsf	$4.04	$2.18	$3.02	$2.90
50,000 gsf	$3.57	$1.57	$2.33	$2.28

Figure 3 shows the differential breakdown of affected elements responsible for these trends. The values shown by the bar sections are the differences between the cost of the category for the UFAD system alternative and the corresponding cost for the OH baseline. Values greater than zero indicate a cost premium for UFAD whereas negative values indicate a cost savings for UFAD in relation to OH. The black line indicates the overall cost differential for each column; the sum of all components. The main driver for the sensitivity in the total differential is the HVAC category with the UFAD HVAC cost for all alternatives decreasing in relation to OH HVAC with increased floorplate size. This graph also shows that as the size of the floorplate increases, the electrical and workstations elements exhibit the opposite trend and become slightly more expensive. This demonstrates how the detailed cost model is able to predict the trend in overall cost differential between UFAD and OH, even when individual elements are impacted in different directions.

Figure 4 illustrates the breakdown of this decrease in HVAC cost vs. increasing floorplate within each system alternative. Note that the perimeter terminals, ducts and diffusers contribute significantly to the cost premium of UFAD HVAC systems over OH. As shown in Table 2, increasing floorplate size yields a lower perimeter to interior ratio, and thus reduces the impact of the perimeter HVAC cost element on the total cost differential for UFAD systems. Figure 4 also shows that each of the individual HVAC cost elements are decreasing (i.e., the premiums for UFAD are decreasing and the savings increasing) with increased gross floor area.

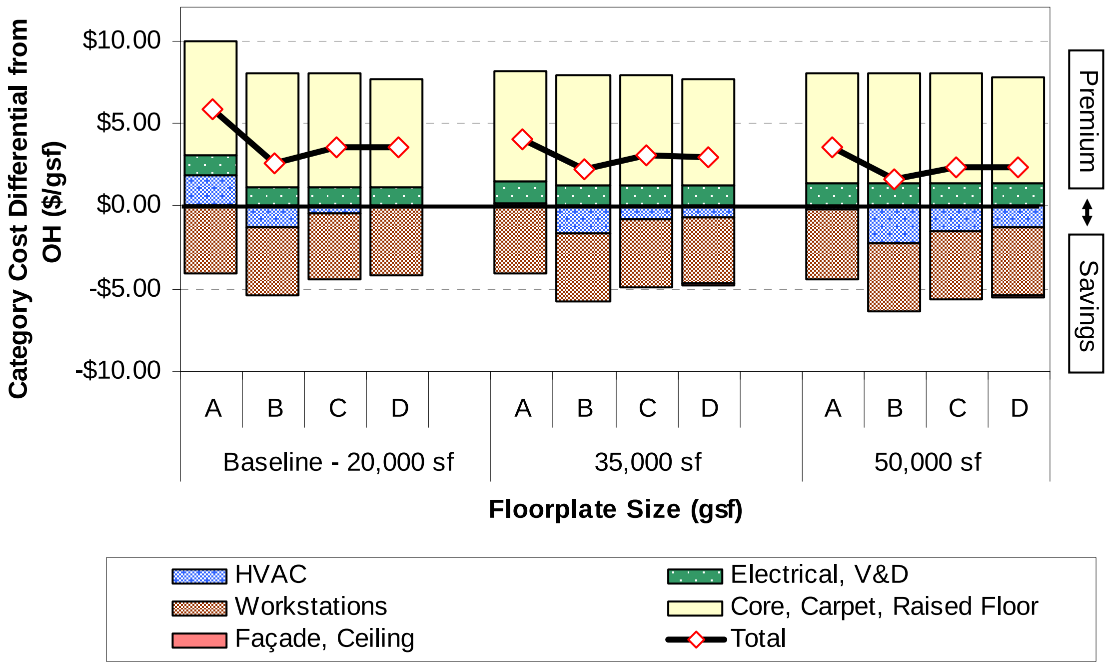


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Figure 3. Floorplate Size: Category Cost Differential Breakdown

All in all, the cost of UFAD systems per square foot decreases with increasing floorplate size with variation largely due to changing HVAC cost. However, as shown in Figure 3, the cost premium for Core, Carpet and Raised Floor as well as the cost savings for Workstations each dwarf the differentials for electrical and HVAC categories and though they change little as a function of floorplate size, they remain sizeable contributors to the overall cost differential. This leads us to the overall conclusion that cost differentials are relatively insensitive to changes in floor area, exhibiting less than a $2/gsf variation over a broad range of typical floor plate areas.

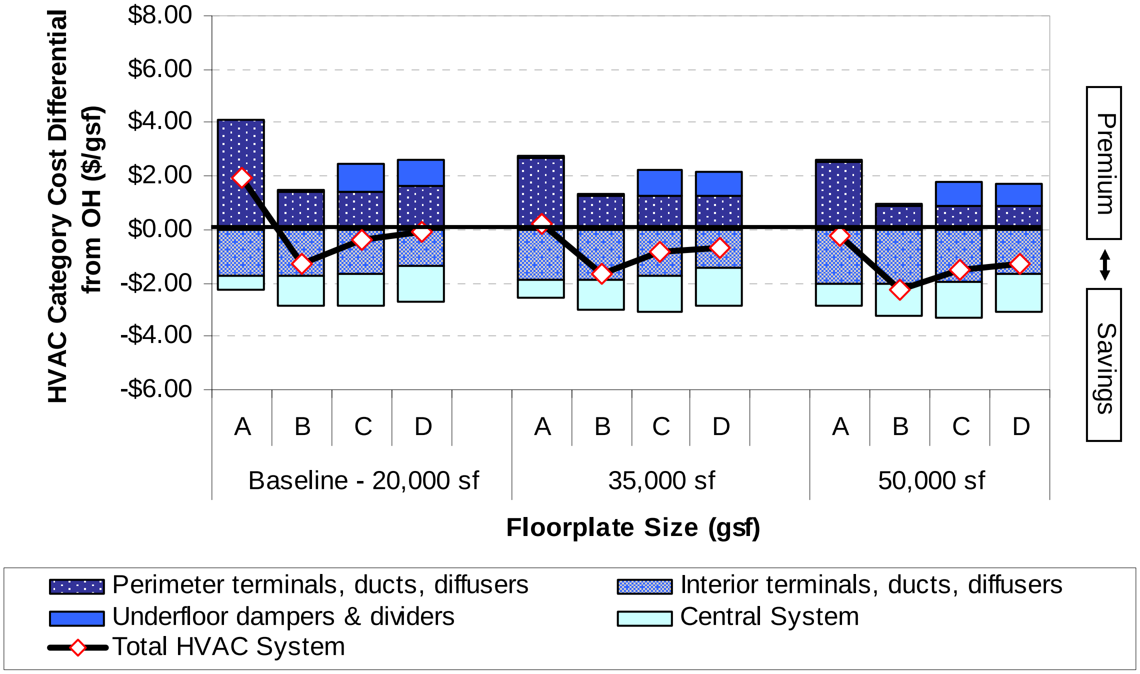

Figure 4. Floorplate Size: HVAC Category Cost Differential

5.1.2 Raised Core

In the first cost model we assume that all UFAD systems will require a raised metal deck core. In this study we looked at the effects of varying the percent of the building that is used as core (5-15%) and subsequently at varying the percent of the core that is raised (25% - 100%). Figure 5 presents the overall cost difference between UFAD systems and the OH baseline, and shows that all UFAD systems experience a relative increase in cost with increasing raised core area compared to OH systems that do not require a raised core. However, the change in cost differential is quite insensitive with variations less than $1/gsf across the range of core areas tested.

Figure 6 shows the results from the second part of the study where we increased the percent of core that is raised, keeping the core area uniform. Again, this graph shows the total cost difference between the UFAD systems and the OH baseline. The range of costs exhibited in this study is again approximately $1/gsf for the values of raised core area tested.

The only category of costs that varies with increasing raised core area is the cost of the raised core itself. Generally, the cost differential between OH and UFAD systems is not very sensitive to these changes in a large part due to the relatively small impact of interior HVAC costs, which are generally dwarfed by the higher cost of UFAD perimeter systems.

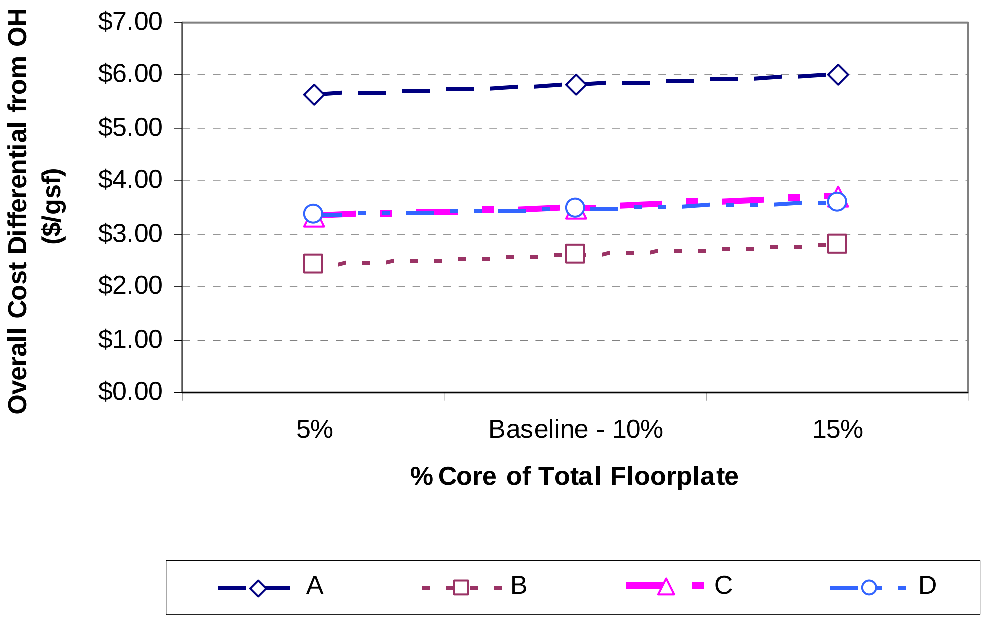

Figure 5. Percent of Floorplate as Raised Core: Total Cost Differential Trend

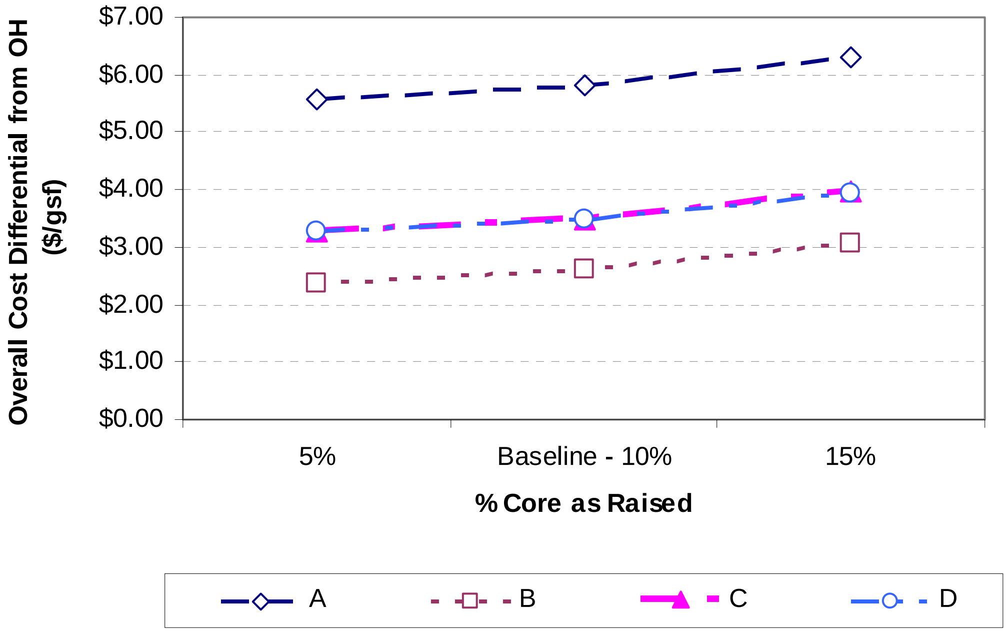

Figure 6. Percent of Core as Raised: Total Cost Differential Trend

5.1.3 ORIENTATION

For the final study in the category of building geometry, we focused on variation of building orientation.

Figure 7 is a schematic diagram of the baseline building footprint showing that the long axis of the building is oriented in the East/West direction. Based on the design assumption of a length to width ratio of 1:1.5, Figure 8 shows the results of turning the building from an East / West axis to a North / South axis by showing the total HVAC cost difference between UFAD and OH for each system. The cost differential between OH and UFAD changes very little (less than $1/gsf) between orientations, as shown in Figure 8.

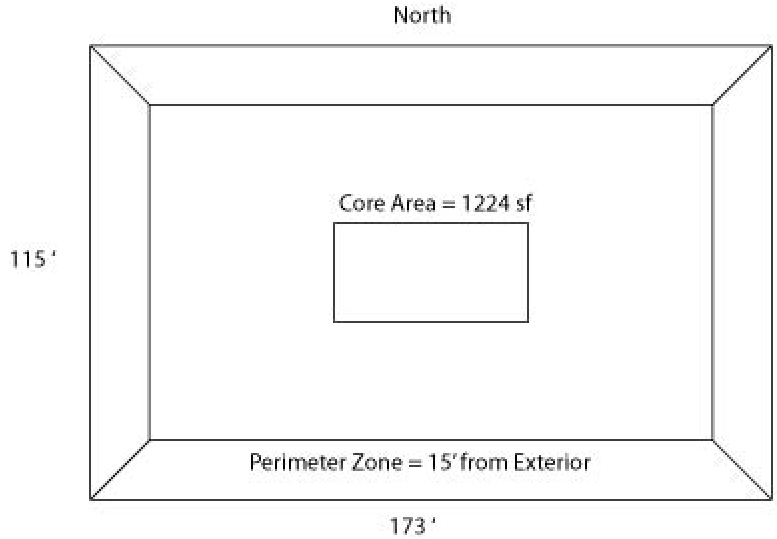

Figure 7. Orientation: Baseline Building Footprint

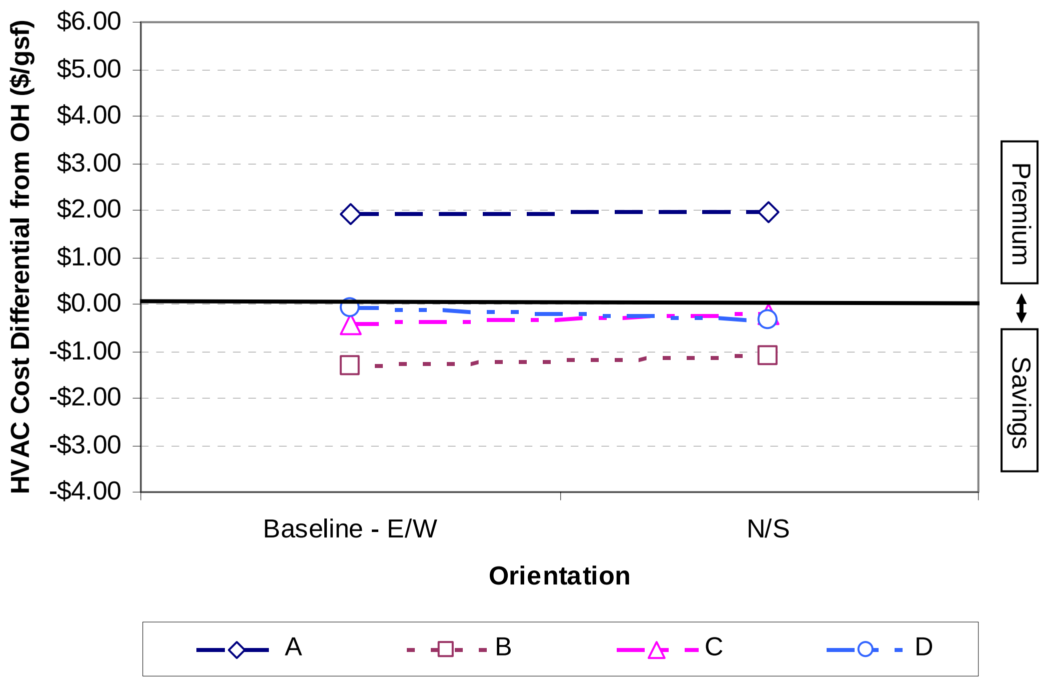

Figure 8. Orientation: Total HVAC Cost Differential Trend

As expected, the only changes in cost occur in the perimeter and central mechanical/HVAC systems whereas the interior mechanical/HVAC system costs remain unchanged. UFAD B and UFAD C change equivalently between orientations because they have the same perimeter HVAC configuration. Additionally, the sensitivity that we observed in the mechanical/ HVAC system is minor compared with the differential between the UFAD systems and overhead system in the workstation and core/carpet/raised floor elements as previously discussed in the Floorplate Size study and shown in Figure 8.

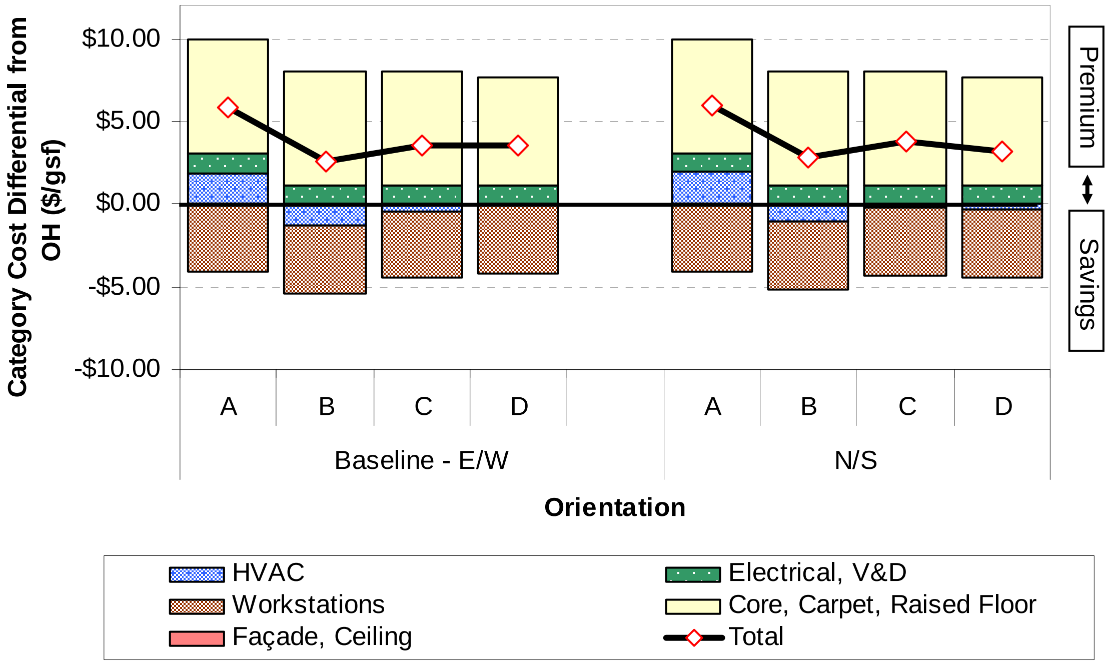

Figure 9. Orientation: Total Category Cost Differential Breakdown

5.1.4 WALL THERMAL QUALITY

In this study we tested the sensitivity of cost to wall thermal quality. The model provides "Good", "Better", and "Best" options for wall thermal quality as shown in Table 4. The "Good" option reflects window and wall specifications that meet ASHRAE 90.1 for the climates shown. The other options reflect higher qualities that exceed ASHRAE 90.1 by 20% and 40%, respectively. As ASHRAE wall quality requirements are set to somewhat equalize the energy use in all climates, the method tends to equalize the wall characteristics for the climates we used. For example in the "best" case, the wall specifications are identical for all climates we used.

In this study, we only varied the wall thermal quality for the San Francisco climate. All other inputs remained at their baseline values. The model does not include a parameter for increased cost of constructing a higher quality wall, as this cost would be equivalent for both OH and UFAD systems. As such, the only affected cost element in this study is the HVAC system.

Since changes in wall thermal quality affect both UFAD and OH systems, we show the results on a total affected cost basis. Figure 10 shows the total HVAC costs for the OH and UFAD systems for each of the three levels of wall thermal quality. Note that all systems decrease in cost by approximately $2-$4/gsf over the given range of thermal qualities with the OH and UFAD D systems exhibiting the least sensitivity to this factor. Systems UFAD B and UFAD C experience the same rate of change as they both have the same perimeter system. Among the UFAD systems, UFAD D experiences the least variation in costs to this and other perimeter conditions as seen by the relatively low rate of change when compared to the other UFAD systems. This is because UFAD D terminal costs (i.e., these are sized by heating load) are not as sensitive to cooling load as the other systems. We summarize the differentials in Table 5 below. This table shows that except for UFAD D, the premium for all systems is reduced as wall thermal quality increases.

Table 4. Wall Thermal Quality: Wall Definitions

		Fenestration						Wall Assembly		
		Good Case (meets 90.1)		**Better Case (meets 90.1 + 20%)**		**Best Case (meets 90.1 + 40%)**		**Good Case (meets 90.1)**	**Better Case (meets 90.1 + 20%)**	**Best Case (meets 90.1 + 40%)**
Climate type	**City**	U_{fixed}	$SHGC_{all}$	U_{fixed}	$SHGC_{all}$	U_{fixed}	$SHGC_{all}$	$U_{assembly}$	$U_{assembly}$	$U_{assembly}$
Hot, humid	Miami	1.22	0.19	0.73	0.19	0.46	0.19	0.124	0.1033	0.0886
Hot, dry	Phoenix	1.22	0.19	0.73	0.19	0.46	0.19	0.124	0.1033	0.0886
Warm, dry, marine	San Francisco	0.73	0.39	0.46	0.25	0.46	0.19	0.124	0.1033	0.0886
Mixed, humid, marine	Baltimore	0.46	0.25	0.46	0.19	0.46	0.19	0.124	0.1033	0.0886
Window to wall ratio (WWR)		**45% WWR**		**40% WWR**		**30% WWR**				

WWR = window to wall ratio; i.e., percentage of the exterior wall that is window.

Figure 11 shows the HVAC cost breakdown for all systems for each level of wall thermal quality. Note that the major change in cost occurs in the perimeter terminals, ducts and diffusers. As the perimeter systems for UFAD are more expensive than for the assumed OH system, the UFAD costs decrease at a greater rate as perimeter loads are reduced.

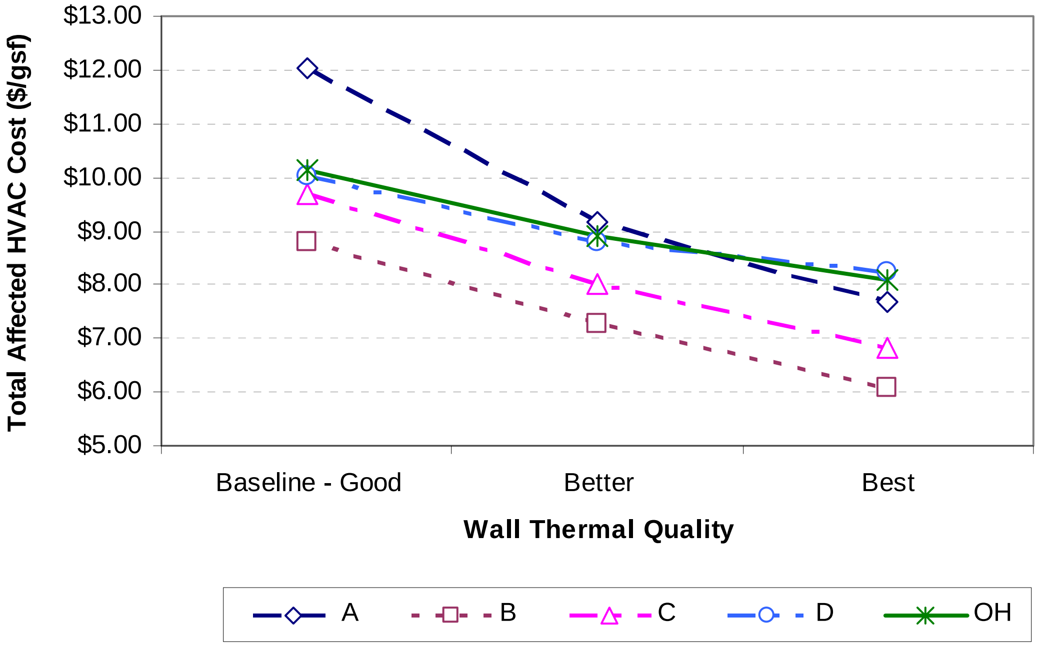

Figure 10. Wall Thermal Quality: Total HVAC Cost Trend

Table 5. Wall Thermal Quality: Total Cost Differentials (UFAD premiums)

UFAD system type	A	B	C	D
Baseline - "Good"	$5.58	$2.37	$3.27	$3.23
"Better"	$3.84	$1.96	$2.70	$3.19
"Best"	$3.09	$1.50	$2.24	$3.45

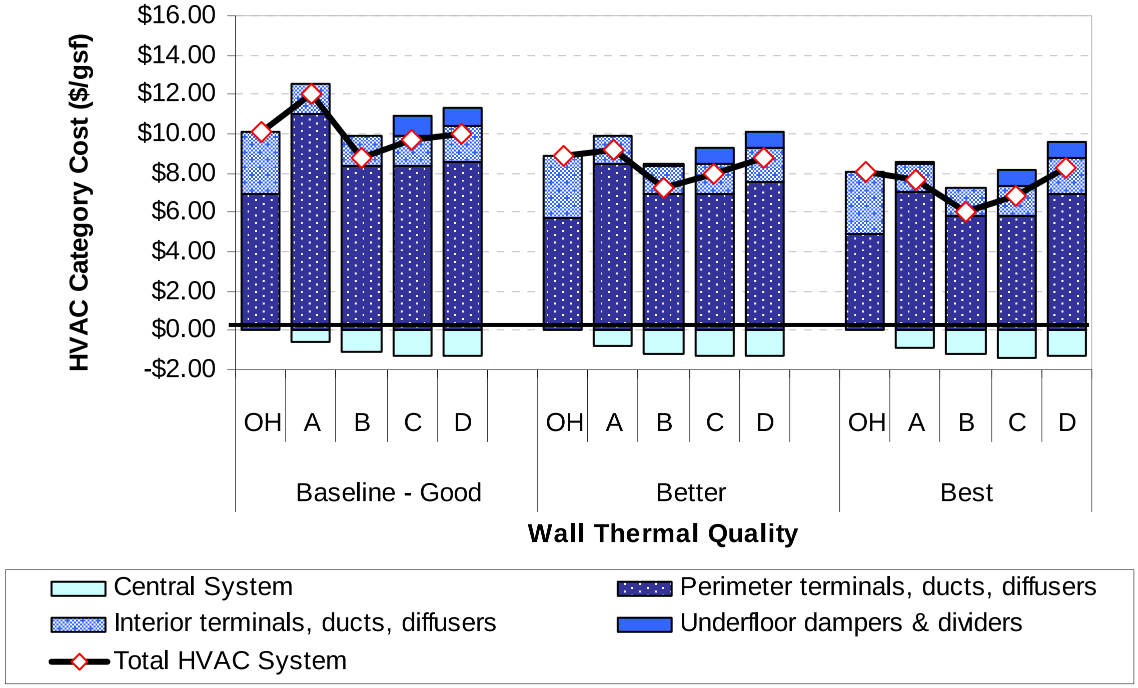

Figure 11. Wall Thermal Quality: Total HVAC Category Cost Breakdown

5.1.5 UFAD Supply Plenum Height

Another cost impact has to do with UFAD supply plenum height. If the floor-to-floor height is kept the same, changing the UFAD supply plenum height will alter the cost of the HVAC system alone. We constructed the model to allow for variation in floor to ceiling height (with a choice between a 9' or a 10' height), UFAD supply plenum height, ceiling treatment, and variation in both the UFAD and OH return air plenum height. In this study we varied just the UFAD supply plenum height to examine the sensitivity of costs of underfloor equipment. Keeping the baseline constant as a steel building with a hung ceiling, we varied UFAD supply plenum height from a low of 12 inches to a high of 18 inches, keeping the floor-to-floor height constant by varying the return plenum height in proportion to the supply plenum change.[2]

Figure 12 shows the cost differential breakdown for variations in supply plenum height. From this graph we can see that the HVAC system experiences an increase in cost in the lower height plenums due to the model assumption that all plenums less than 16" in height will use "low-height" equipment, thus adding a cost premium (due to increased number of units) for lower plenum heights.

[2] We subtracted the effect of the change in façade cost due to the slight change in floor-to-floor height.

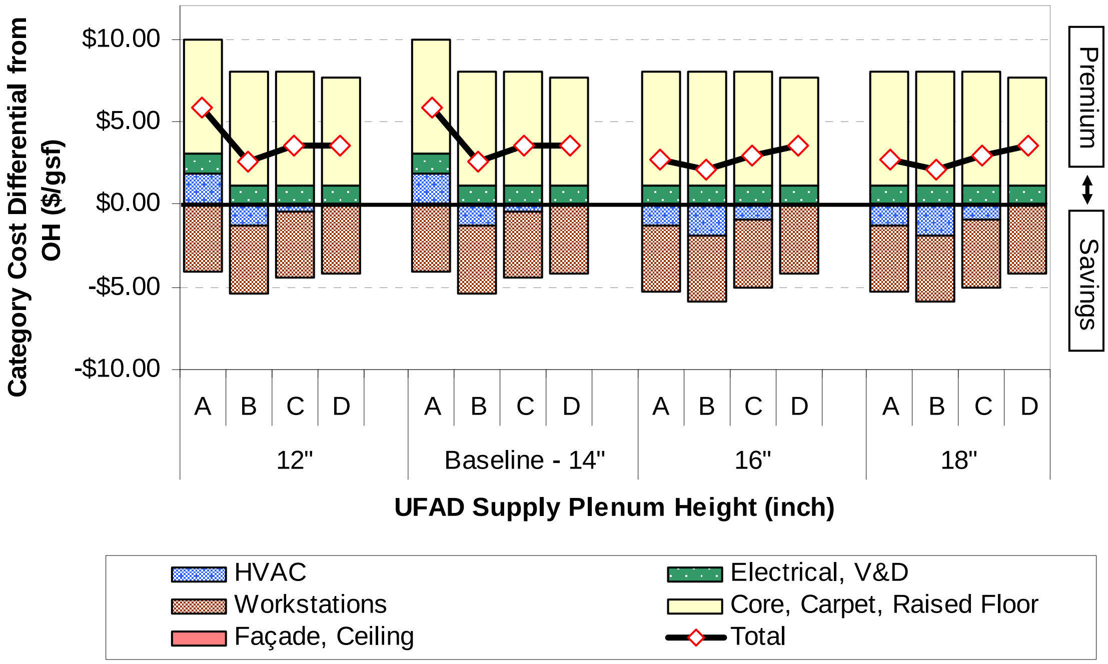

Figure 12. Wall Height Savings: Total Category Cost Differential Breakdown

5.1.6 Wall Height Savings

A potential savings in using a UFAD system results from the ability to decrease the floor-to-floor height by decreasing or eliminating the overhead return plenum in the UFAD system. We tested the sensitivity of this element by varying both ceiling treatment and return air plenum height, as the potential for varying the height of the return plenum changes dependent upon which ceiling treatment is in place. A return air plenum height of 0 indicates an exposed ceiling. In this model, we assume that the exposed ceiling is only an option for UFAD systems with respect to wall height savings; the OH system has a hung ceiling.

Figure 13 shows the assumptions used for the minimum return air plenum configuration for an UFAD building. Note that the minimum return air plenum height in a steel building for UFAD is 2 ft and for a concrete building is 0 (exposed ceiling).

Figure 14 shows the minimum return air plenum heights for an OH building where a minimum of 2 ft is required for a return air plenum in a concrete building a 24 inch (3.2 ft) is required in a steel building. In our baseline, we model the OH steel building with a 3.2 foot return air plenum to balance with the 14" supply plenum height for the UFAD system, thus resulting in equal floor to floor heights.

Figure 15 shows the cost differential breakdown for these changes in ceiling treatment and return plenum height. The first scenario shown is the baseline that assumes a steel building with a hung ceiling for both OH and UFAD systems, using the minimum return air plenum height for each. The second and third scenarios assume a UFAD concrete structure with a hung ceiling (1 ft return plenum) and exposed ceiling (no return plenum, thus a 2 ft wall height savings), respectively. We show the cost differential results in Table 6. Overall, the results show that only when wall height decrease is greater than about 1 ft is there a savings in the façade affected element with a $1.38/gsf savings for 2 ft wall height savings as seen in Figure 12. However, even this savings is not large enough to result in more than a negligible net savings for UFAD over OH.

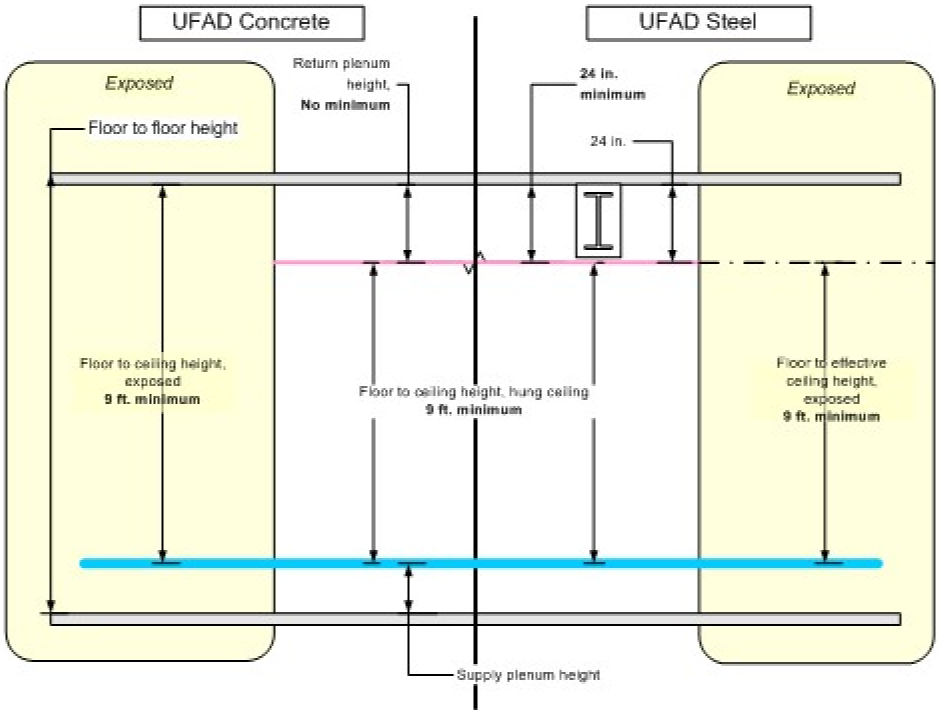

Figure 13. UFAD Return Air Plenum Configuration

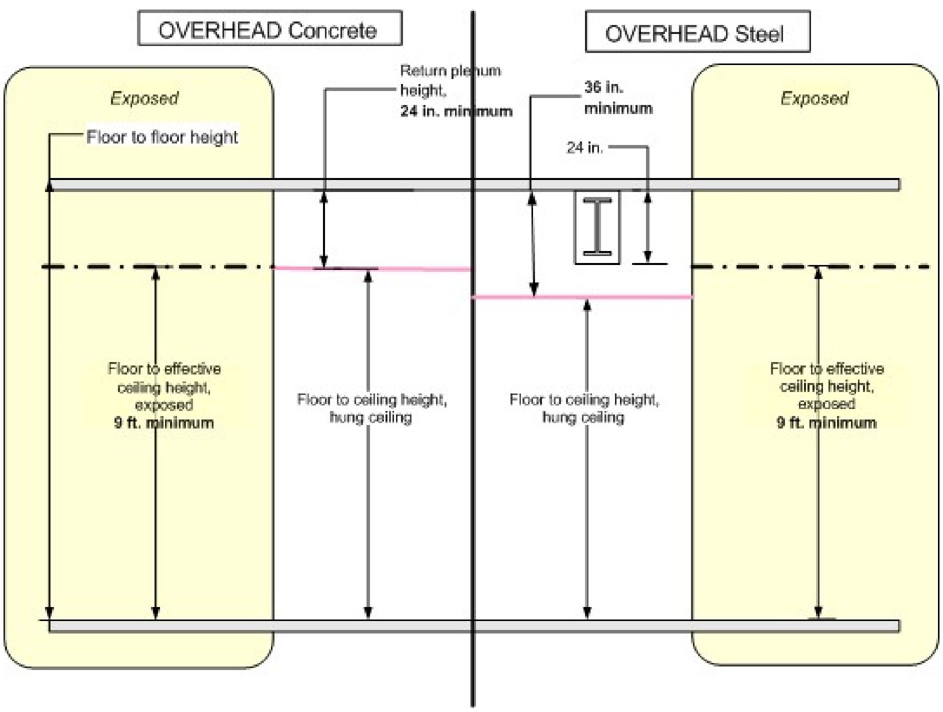

Figure 14. OH Return Air Plenum Configuration

Table 6. Wall Height Savings: Total Cost Differentials

Scenarios showing RA plenum heights	Wall height savings, ft	A	B	C	D
Baseline, UFAD steel, 2 ft OH steel, 3.17 ft	0.0	$5.82	$2.60	$3.50	$3.49
UFAD concrete, 1 ft (hung) OH steel, 2 ft	0.83	$4.63	$1.43	$2.32	$2.33
UFAD concrete, 0 ft (exposed) OH steel, 2 ft	2.0	$2.63	-$0.60	$0.30	$0.29

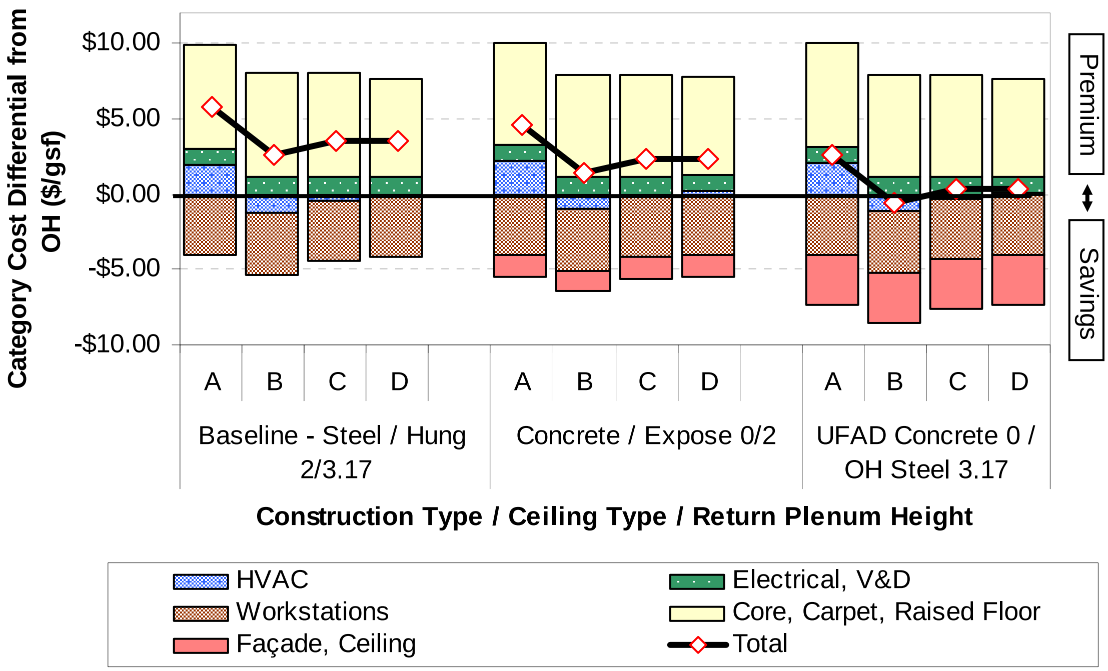

Figure 15. Wall Height: Total Category Cost Differential from OH Breakdown

5.1.7 Material and Labor Rate

For our baseline model we assume material and labor costs based in San Francisco, one of the higher cost cities in the U.S. We ran the baseline configuration using the labor costs and materials of five different cities including the most costly (New York City) with respect to labor and one of the least costly (Charlotte, NC) to explore the impact of material and labor rates associated with different locales. Table 7 shows the material and labor indexes we used for each city derived from the RS Means Cost Estimating manual [RS Means 2004].

Table 7. Material and Labor Index

City	% Material	% Installation
New York City	109.1%	161.3%
San Francisco	110.7%	139.3%
Portland	103.9%	109.5%
Cincinnati	94.6%	90.2%
Charlotte	97.2%	56.8%

Figure 16 shows the total affected cost for all systems relative to the city used to calculate labor and material costs. The graph shows that though absolute costs experience a great change, the relationship between the different systems remains similar. This graph shows the overall price range per square foot changing by approximately $13-15/gsf depending on the city, though, as expected, all system lines experience these changes in labor and material cost similarly. However, Table 8 shows that, except for UFAD A, the differential between UFAD and OH increases as labor and materials rates are reduced; the range is ~$1-2/gsf increase in UFAD premium as the rates decrease from most expensive to least expensive. These results also provide insight into why it is difficult to compare specific projects from different locations on an apples-to-apples basis without accounting for differences in local material and labor rates. The sizeable range of cost impacts shown in Figure 16 is equal or larger than many of the other cost variations due to typical design options.

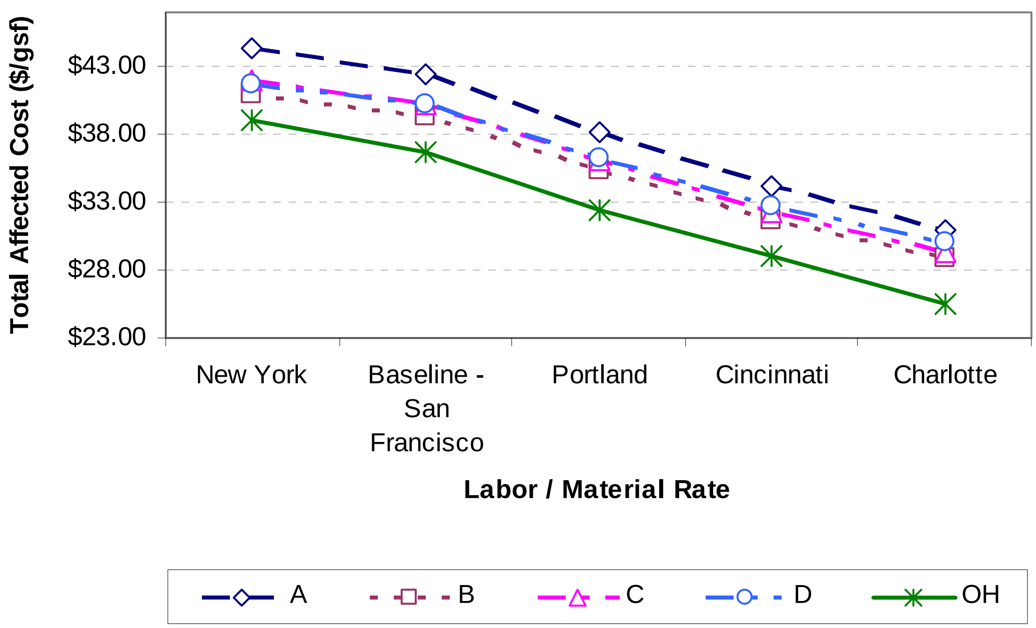

Figure 16. Labor Rate: Total Affected Cost Trend

Table 8. Material and Labor Rate: Total Cost Differential from OH ($/gsf)

UFAD system types	A	B	C	D
New York City	$5.28	$1.83	$2.86	$2.59
San Francisco	$5.82	$2.60	$3.50	$3.49
Portland	$5.74	$2.94	$3.65	$3.93
Cincinnati	$5.16	$2.69	$3.28	$3.69
Charlotte	$5.54	$3.42	$3.81	$4.64

Table 9. Material and Labor Rate: Total Cost Differential from New York City ($/gsf)

System type	OH	A	B	C	D
San Francisco	-$2.38	-$1.84	-$1.61	-$1.74	-$1.48
Portland	-$6.67	-$6.22	-$5.56	-$5.88	-$5.33
Cincinnati	-$10.05	-$10.17	-$9.20	-$9.64	-$8.95
Charlotte	-$13.62	-$13.36	-$12.03	-$12.67	-$11.57

5.1.8 WORKSTATION SIZE

For the baseline model, we assume a typical workstation size of 8 ft x 8 ft for all open office areas. Many other studies in this paper have shown that the difference in the cost of workstations between overhead and underfloor systems is significant and often results in a greater impact on total differential than other system categories such as HVAC and Facades. This should result in an increase in sensitivity to any factors that change the number of workstations. We investigated this sensitivity directly by varying the size of workstations.

The baseline price for OH workstations is greater than that of the UFAD systems because we assumed that all overhead system workstations are equipped with powered furniture (a common configuration in today's buildings) while UFAD systems have the option of powered-or non-powered. We assume a conventional electrical configuration for UFAD systems (as opposed to modular). Each of these options has different implications for the electrical and V&D costs as well as the furniture cost. Since no cost categories other than the workstation costs of electrical, voice and data, and furniture were affected in this study, we limit the results presentation to these two categories only as shown in Figure 17.

Figure 17 shows a breakdown of material and labor costs related to changing workstations. The values shown are the difference between UFAD (all UFAD systems are equal in this category) and OH for electrical and furniture. As Figure 17 shows, overall total workstation cost savings decrease by only $0.54/gsf as workstation size is increased from 8 ft x 8 ft to 10 ft x 10 ft. This results from the counterbalancing effects of a *decrease in electrical premiums* in combination with a *decrease in furniture cost savings* (due to reduced number of workstations).

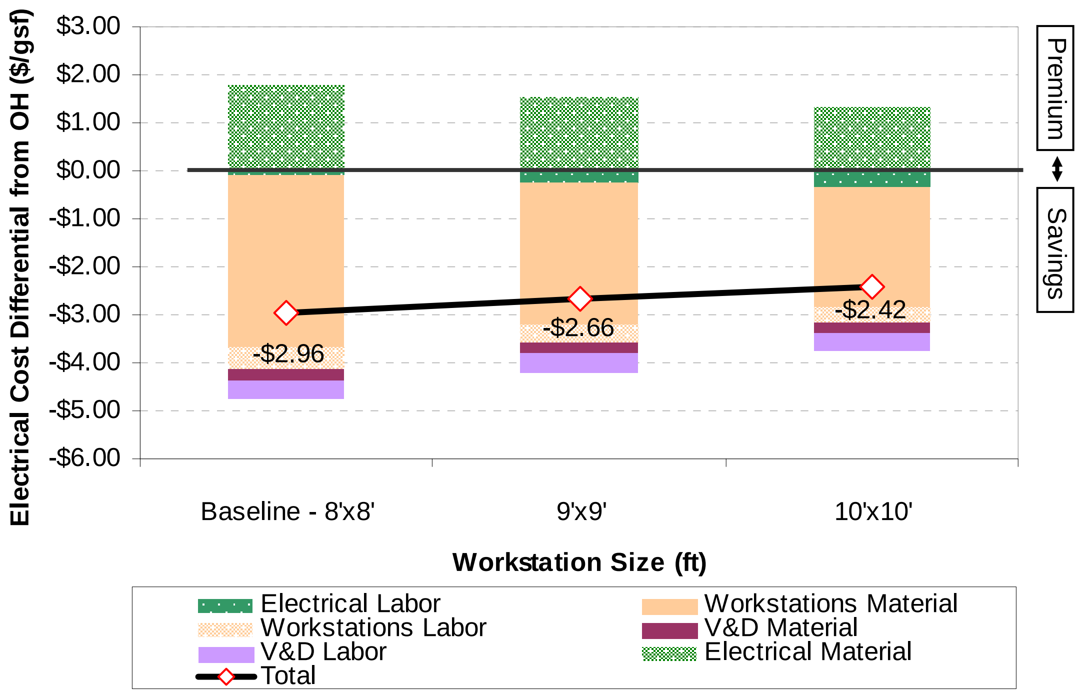

Figure 17. Workstation Size: Electrical, Voice and Data Breakdown

5.1.9 ELECTRICAL

The electrical design options that we have incorporated into the first cost model are centered on options for workstation power distribution, voice and data wiring, and powered vs. non-powered furniture. The model includes options for modular and conventional wiring for UFAD systems, each with the option of either powered or non-powered furniture. The model allows two options for electrical in the OH system – either poke-thru or power-pole configurations. Both of the OH options require powered furniture because this is the most common configuration for OH systems. In this study we varied the options for UFAD while assuming that the baseline OH system used power-pole distribution with powered furniture. Additionally, we included the option to use labor rates for raised floor installers in two scenarios.

Figure 18 shows the material and labor cost breakdown for the elements affected by electrical configuration changes. The chart shows that, compared to the OH option, all UFAD configurations exhibit a cost savings largely due to a reduction in workstation material and electrical and V&D labor. The data labels indicate the total savings between the given UFAD scenario and the OH baseline. Note that the electrical material and labor costs are significantly greater in the all cases of the UFAD non-powered furniture option, but this cost premium is outweighed by the large savings in workstation material. Also, the difference between modular wiring and conventional wiring for UFAD is negligible due to trade offs between labor and material. Finally, the use of raised floor labor and materials reduces the costs by an additional $1-1.50/gsf.

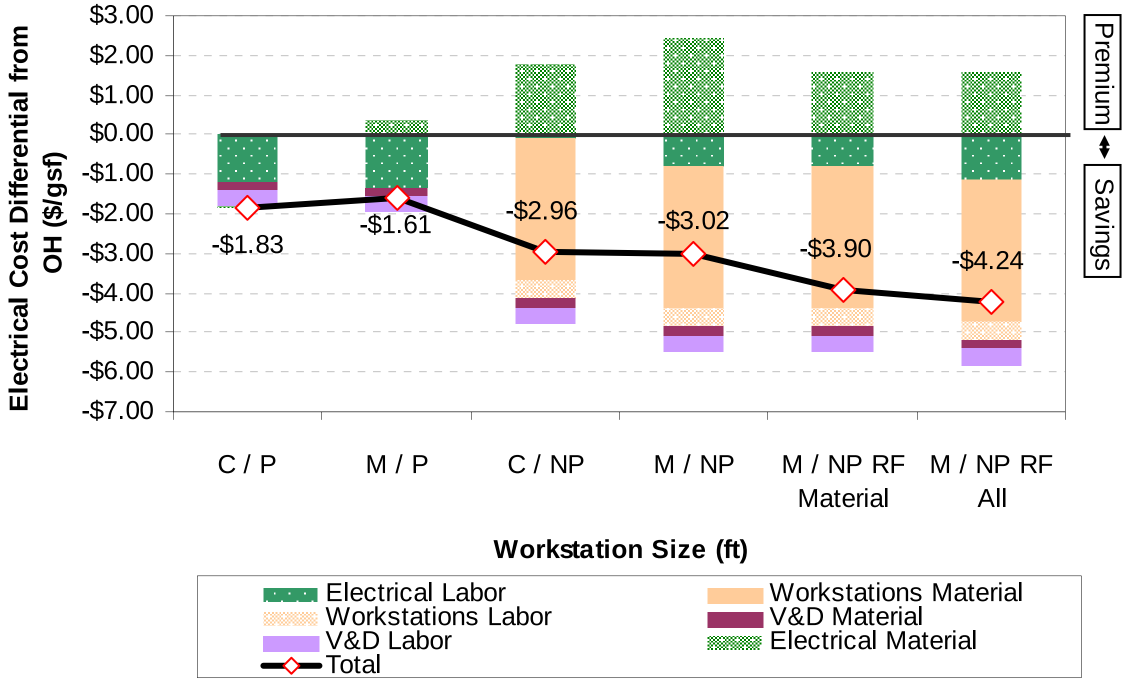

Figure 18. Electrical: Total Workstations, Electrical and V&D Cost Breakdown

Where:

C = Conventional Wiring

M = Modular Wiring

P = Powered Furniture

NP = Non-Powered Furniture

RF = Raised Floor provider supplied the material (and in the final scenario, labor as well)

5.2 HVAC

5.2.1 Envelope: Climate

One of the larger points of discussion regarding UFAD systems is the question of how to deal with perimeter loads. To study this, we looked at the influence of varying climate on cost, focusing especially on the impact to the perimeter HVAC system. In this study, we set all wall thermal quality properties equal to the, “Good,” levels (Table 4) and varied the climate between San Francisco, Baltimore, Phoenix and Miami. We did not change the corresponding material and labor rates, so all results are expressed in San Francisco prices but reflect the envelope loading of the corresponding climate.

Figure 20 shows the total HVAC cost for all systems with respect to changing climate. The trend shown here is similar to that exhibited previously in the, “Orientation,” and, “Wall Thermal Quality,” studies where OH and UFAD D are the least sensitive to this changing perimeter condition, and UFAD A is the most sensitive. UFAD B and C costs change in the same way as they have the same perimeter system. UFAD D is the least sensitive of the UFAD systems due to the difference between this system and the others with regard to terminal fan coil unit costs. Since the model chooses wall properties based on the climate, the results show higher costs in San Francisco due to the poorer wall quality assigned to this climate (see wall thermal quality, Table 4). Figure 21 shows the breakdown of these HVAC costs for all systems. The perimeter category is the only one changing, but it is important to note that this category makes up the largest portion of the costs for all the systems, and therefore has the most significant impact on overall system costs, and thus the differentials.

Figure 19 shows the total affected cost differentials between OH and UFAD for these four climates. These results indicate that when buildings are designed according to ASHARE 90.1 criteria (and labor rate differences are ignored) the relationship between UFAD HVAC costs and OH HVAC costs remains fairly uniform between climates.

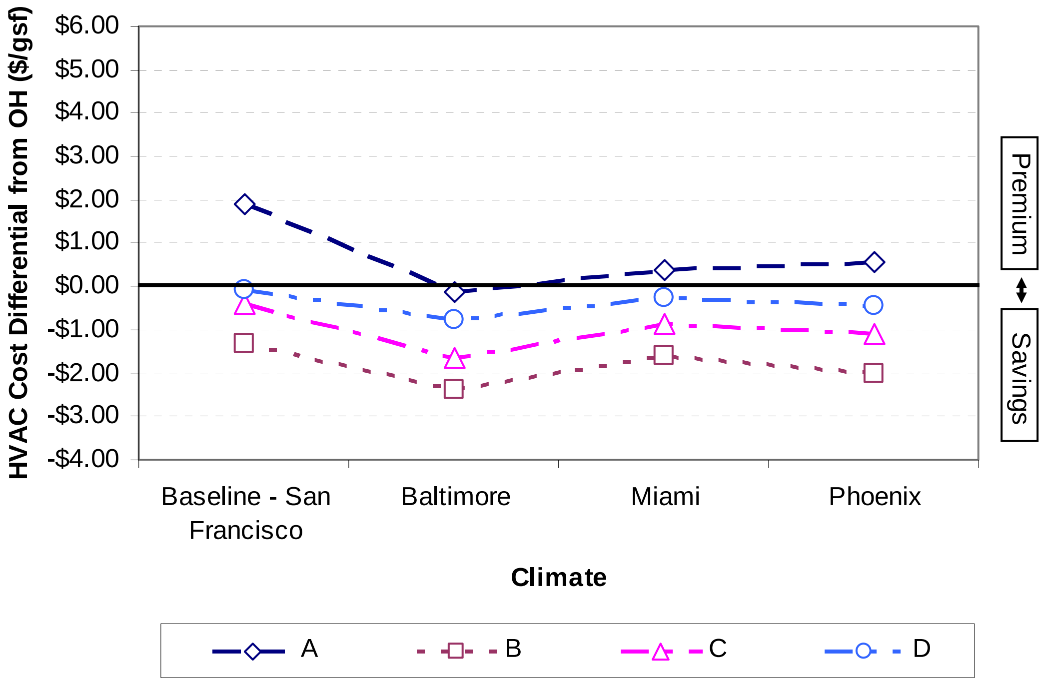

Figure 19. Climate: Total Affected Cost Differentials

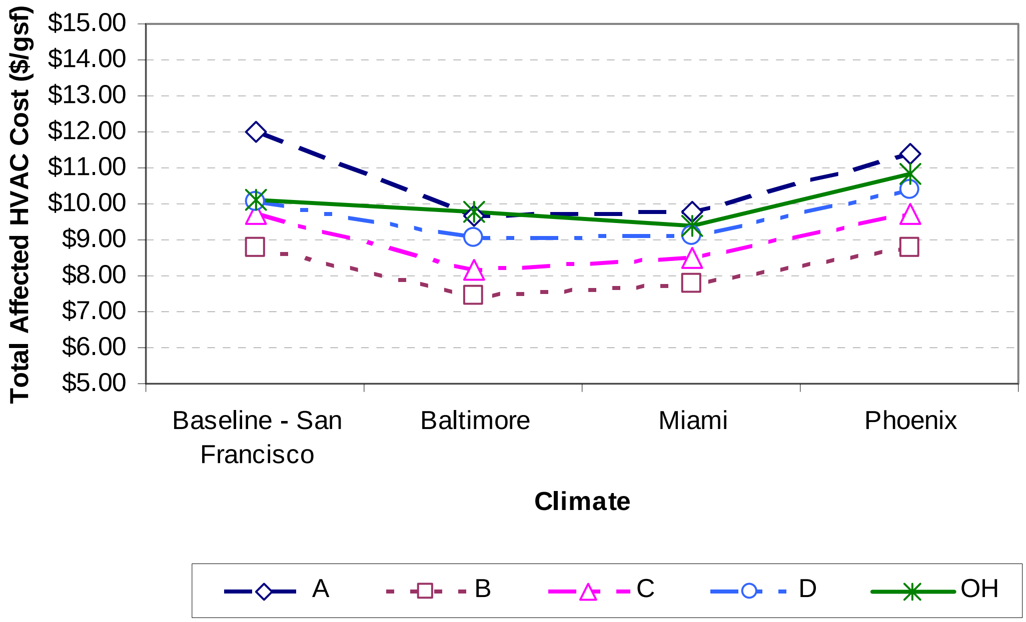

Figure 20. Climate: Total HVAC Cost Trend

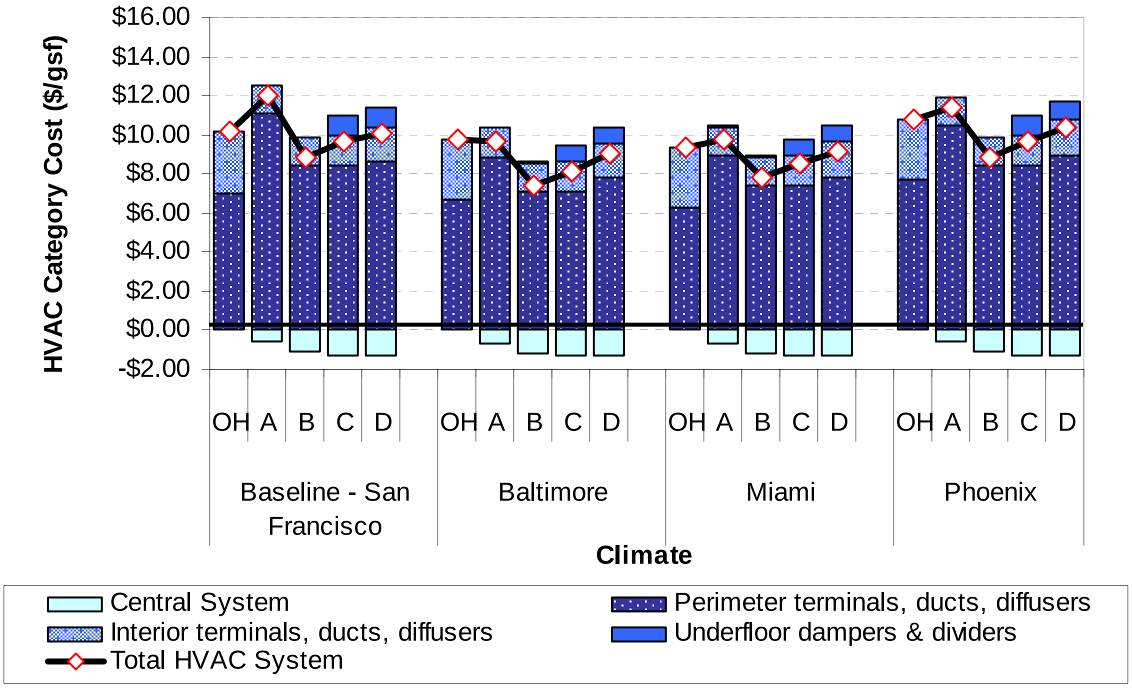

Figure 21. Climate: Total HVAC Category Cost Breakdown

Table 10. Climate Study: Affected Cost Differentials Summary

UFAD System type	A	B	C	D
San Francisco	$ 5.55	$ 2.33	$ 3.23	$ 3.22
Baltimore	$ 3.17	$ 1.46	$ 1.92	$ 2.79
Miami	$ 4.07	$ 2.59	$ 3.00	$ 3.79
Phoenix	$ 4.54	$ 2.61	$ 3.13	$ 3.96

5.2.2 ZONING: PRIVATE OFFICE AREA

We used the first cost model to conduct a number of different zoning studies in order to understand how zoning design options impact the cost of UFAD. In this study we assumed that a roughly equal percentage of area in the interior and the perimeter was dedicated to private offices. We fixed the number of private offices per zone at five. This affects both OH and UFAD perimeter systems, but only OH systems in the interior. In this study, we imposed no interior zoning on the underfloor systems (the interior was modeled as one large zone, including the private offices) and also imposed no limit on OH VAV box size for OH in the interior to allow for a fairer comparison between OH and UFAD systems for interior spaces. This lack of VAV box size limit on the OH interior zone results in a different baseline for the private office studies than for those discussed above. Therefore, the results reflect the combined impact of changes in cost of OH HVAC and number of workstations. We then varied the percentage of private offices (roughly the same in both the interior and the perimeter spaces).

This study also complements the Floorplate Size study in that it illustrates the effects that would have occurred with increasing floorplate if we had not scaled the private office proportion to stay constant with increased floorplate. The norm would most likely be that a larger floorplate would result in a correspondingly lower proportion of private offices. That effect is more easily studied here, as we scale the area of private office in relation to a fixed floorplate area.

Figure 22 shows the overall cost difference between each of the UFAD systems and the OH baseline for varying levels of private office. We found, as shown, that there is little impact on overall cost differential.

Figure 23 shows the breakdown of these cost differences in the affected elements. The chart shows that although UFAD HVAC costs are reduced relative to OH, furniture cost savings decrease (i.e., UFAD loses its advantage when the number of open plan workstations are reduced as the number of private offices increases). The net result is a relatively steady overall differential due to these counterbalancing changes.

Figure 24 shows the trend for the HVAC costs for all systems. UFAD HVAC costs remain relatively constant, but OH increases due to additional terminal devices required for the 5 offices per zone specification. However, as Figure 22 shows this has little impact on the overall differential.

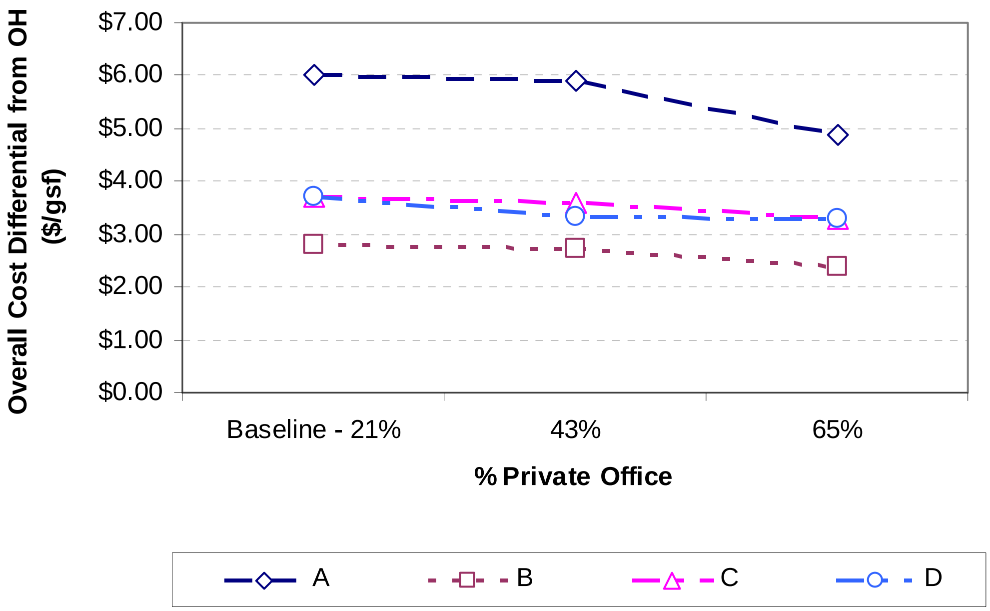

Figure 22: Private Office: Overall Cost Differential

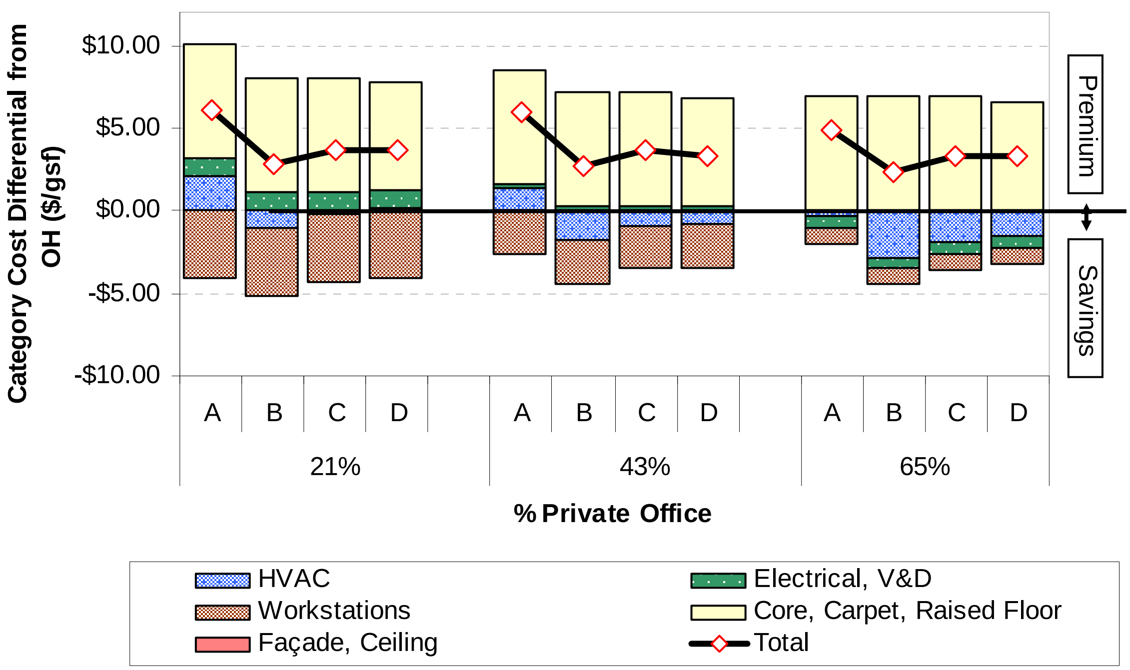

Figure 23: Private Office: Total Category Cost Differential

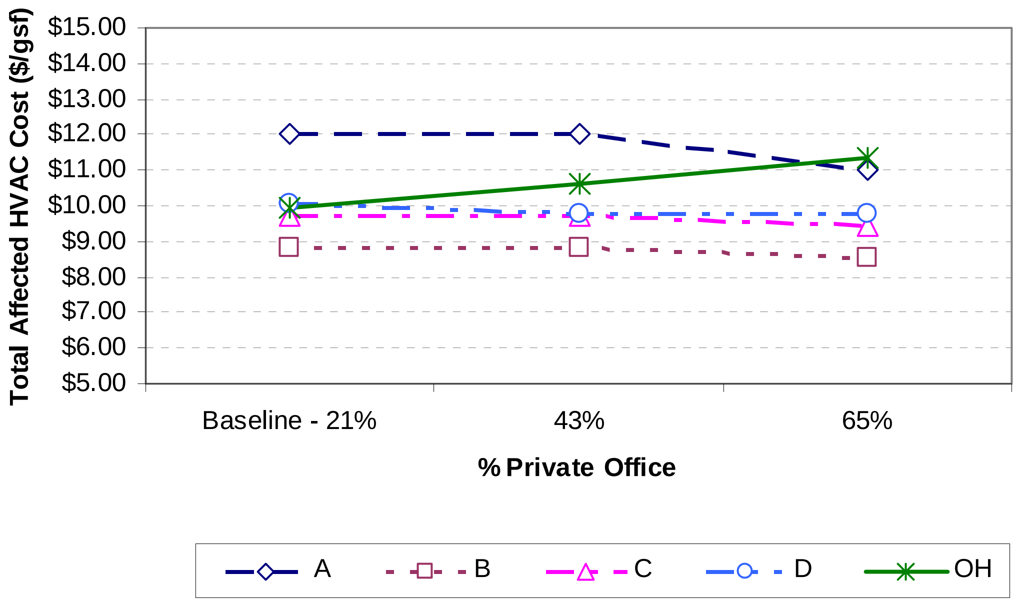

Figure 24. Private Office: Total HVAC Category Cost

5.2.3 Perimeter Private Office

In order to test the sensitivity to perimeter private office alone (without the influence of increased interior zoning for OH), we then conducted another series of runs where the interior space was held at 19% private offices; we varied only the percent area dedicated to private office in the perimeter space. Again, we eliminated the limit on OH VAV box size in the interior space to allow for a more fair comparison between UFAD and OH systems, as the limit artificially imposes more zoning for OH than on UFAD systems.

Figure 25 shows the overall cost difference between the UFAD systems and the OH baseline. The graph shows very little impact on total costs due, again, to the counterbalancing of HVAC and workstation cost differentials. Cost savings due to workstations decrease as private offices increase. Overall, there does not appear to be much cost sensitivity to the number of private offices given the assumptions we have used in this and the previous study, especially because we did not manipulate zoning. Zoning variations are explored in the following studies.

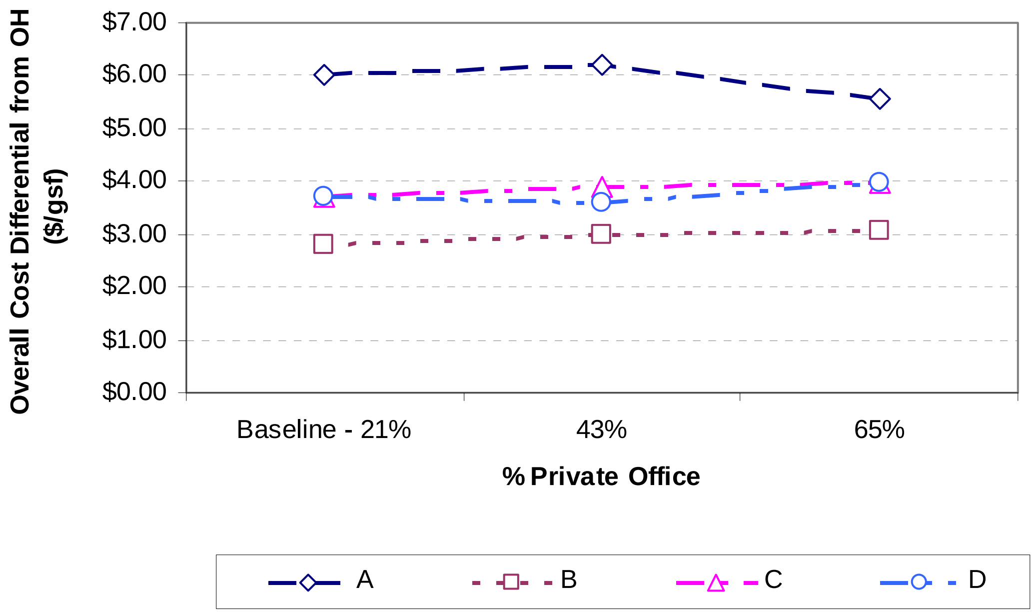

Figure 25. Perimeter Private Office: Overall Cost Trend, 21% PO interior

5.2.4 UFAD C Interior Zoning

One of the potential advantages of an UFAD system is the increased ability to zone spaces cheaply. This study was meant to test this potential benefit. We constructed the model such that zoning could be calculated for OH and UFAD systems separately such that they may not always have the same number of zones. OH systems are likely to be able to have larger perimeter zones because UFAD system zone sizes are limited by the equipment size that may be installed under the raised floor, whereas UFAD systems are likely to be able to have larger interior zones as underfloor plenum zones can be larger and they do not require reheat.

UFAD C is the only UFAD system zoned using plenum dividers on the interior. UFAD A and UFAD B have constant volume systems serving the interior and UFAD D has modulating supply diffusers. A minimum level of zoning is built-in to the assumptions for UFAD D by providing controls to support ten diffusers per zone.

Figure 26 shows the total HVAC cost difference between all UFAD systems and the OH baseline for an increasing number of interior zones. The graph shows no change in HVAC cost for all systems except for UFAD C which increases in cost significantly with higher levels of zoning. We've included the cost information for all UFAD systems to show the relative cost differential of each even as UFAD C costs increase. The premium for UFAD C when interior zoning increases from 4 zones to 16 is about $1.50/gsf. However, when the number of interior zones is equal to four or less, there is virtually no variation in HVAC costs for all systems.

Figure 27 shows the HVAC differential cost breakdown and explains this increase in UFAD C costs at higher levels of zoning due to the rising cost of dampers and dividers needed to partition the interior UFAD plenum.

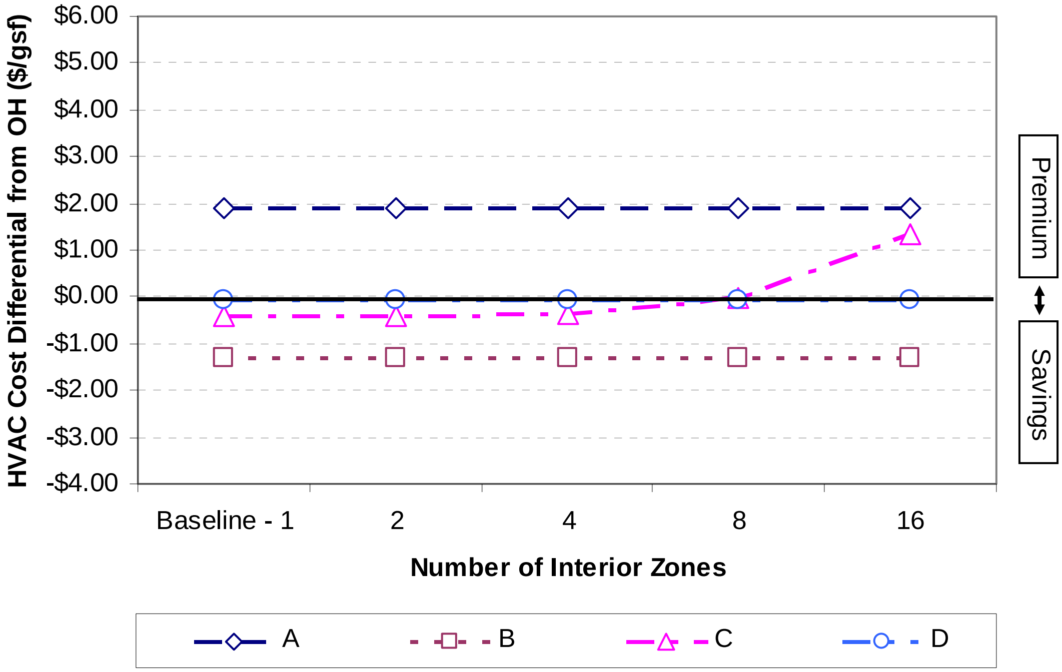

Figure 26. Interior Zones: Total HVAC Cost Differential from OH Trend

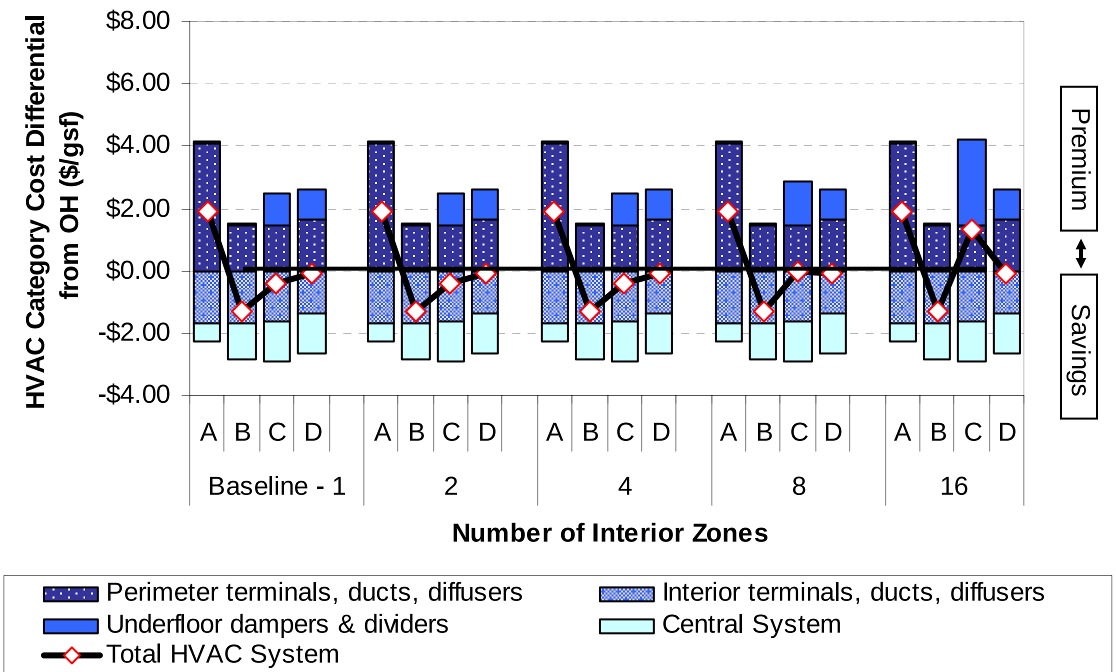

Figure 27. Interior Zones: Total HVAC Cost Differential Breakdown

5.2.5 PRIVATE OFFICES PER ZONE

Whereas the model allows the number of interior zones to be specified for UFAD systems, the "private offices per zone" (PO/zone) parameter accomplishes the same thing for overhead systems for both interior and perimeter spaces. For the baseline model we assumed zoning at 5 private offices per zone with the ability for the user to increase zoning to 3 or even 1 private office per zone. In this study, UFAD interior zoning was not varied thus the sensitivity shown is a function of perimeter zoning only. [3]

Figure 28 shows the total perimeter HVAC cost trend for increased density of zoning (the inverse of private offices per zone). As the zoning increases (from 5 to 1 PO/zone), the cost of the perimeter overhead HVAC system increases because more terminals are used to support the dense zoning. However, it is apparent that there is no effect in the range of typical configurations of 3 to 5 for UFAD systems and only a minor difference for OH. Most likely this occurs because the increased density from 5 to 3 is not large enough to require a change in terminal equipment sizes. One private office per zone is probably not realistic for most buildings, but our results indicate that the difference between 3 (or 5) and 1 PO/zone for an OH system is $3.16/gsf.

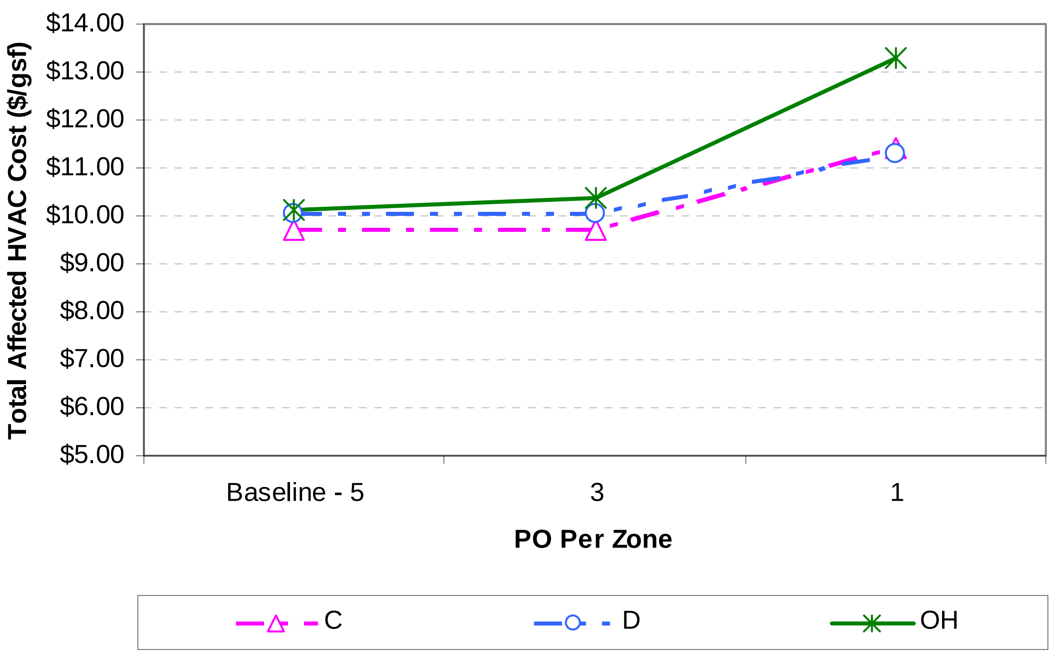

Figure 28. Private Offices per Zone: Perimeter HVAC Cost Trend

5.2.6 ZONING: LIMITING OH VAV BOXES TO 1500 CFM

The baseline assumptions of the model call for a limit of 1500 cfm capacity for OH VAV boxes to limit noise. This study explores the impacts of altering this baseline to allow for no limit. (i.e., limited only by the available sizes of the boxes in our database). We varied no UFAD parameters in this study.

Figure 29 shows the impact on interior and perimeter OH HVAC costs of removing the limit. In the figure "Yes" means with the limit imposed and "No" means with the limit removed. Generally, removing the limit reduces overhead HVAC costs by $1.50-2/gsf. As may be expected, restricting the capacity for the overhead VAV boxes raises the cost of the overhead system and thus lowers the cost differential

[3] Since the PO/zone parameter is applied globally (i.e., to both interior and perimeter) but does not have any bearing on interior UFAD systems, we are showing only perimeter results where there exists a more fair comparison.

between the UFAD systems and the overhead baseline. We tested the effects of removing this limit at three different percentages of area dedicated to private office to show the impact over a broad range of PO ratios. These results can be used directly to compliment other studies in this report by adding a “box limit factor” of $1.50-2/gsf to the results of other studies as a premium for UFAD.

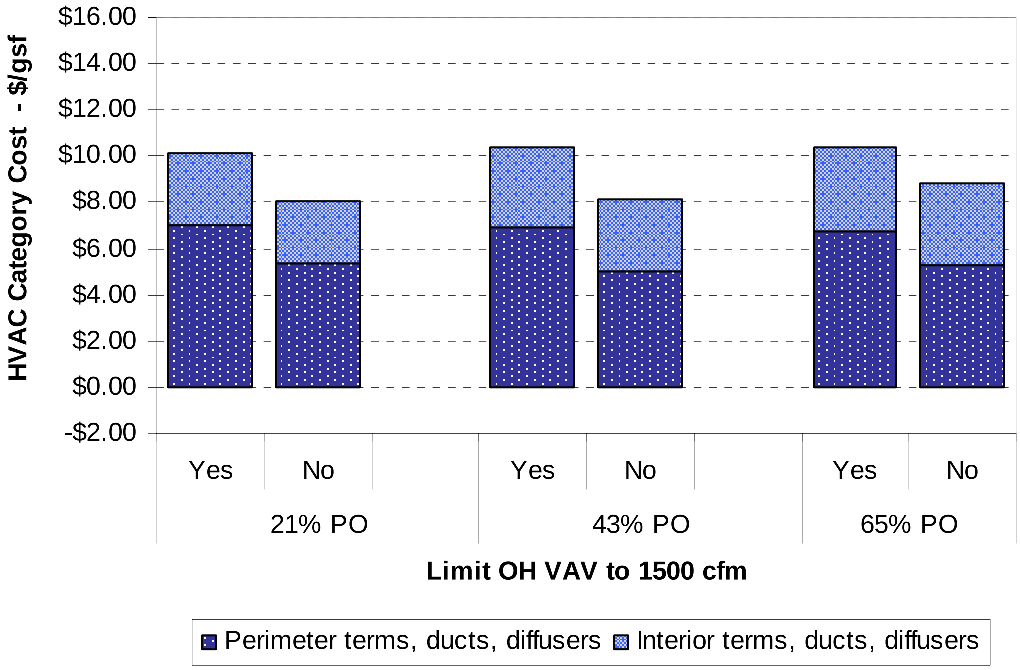

Figure 29. Limit OH VAV Box Size: OH HVAC Cost Breakdown

5.2.7 EQUAL ZONING

The model contains options to provide for different zoning criteria for OH and UFAD systems, as demonstrated in the previous studies. Working on the assumption that equal comfort between the two systems would be signified by an equal number of zones, we iteratively determined the combination of input variables that resulted in a close correspondence between OH and UFAD with regard to the number of zones (both interior and perimeter) for each of the systems in order to compare OH and UFAD on an equal zoning basis.

Table 11 shows a summary of the scenarios we modeled to compare zoning at each of three private office percentage levels (equal fraction of private offices in both the perimeter space and interior space) in an attempt to create equal zoning between OH and UFAD. As systems UFAD A and UFAD B have no interior zoning, we left them out of this study.

Table 11. Equal Zoning: Design settings and zoning comparison

% PO, overall	21% PO	43% PO	65% PO
Design parameters			
1500 cfm limit on OH VAV box size	Yes	Yes	Yes
# PO/zone	5	5	3
# Interior zones for UFAD-C	8	8	16
# PO interior	15	22	35
Zoning comparison			
Total perimeter zones, UFAD-C	23	23	22
Total perimeter zones, OH	23	23	22
Total interior zones, UFAD-C	12	12	20
Total interior zones, OH	13	15	23

Figure 30 shows the total HVAC cost for OH and UFAD C for each of these three scenarios. This graph shows that for spaces with a low to moderate number of private offices there is negligible difference between OH and UFAD when the systems have roughly equivalent zoning between UFAD and OH, although the HVAC cost overall is still greater than for unequal zoning. As the number of private offices increase (i.e., 67%) UFAD C remains less costly than OH. Due to the manner in which zoning is set up in the model, it is not possible for us to create a scenario for UFAD D with a sufficiently equivalent zoning configuration to compare to those above, though it seems that cost trends for UFAD D would fall in between UFAD C and no change.

Figure 31 shows the HVAC category cost breakdown for these three scenarios. The graph shows that much of the cost impact is due to interior terminals, ducts and diffusers for all systems; the added cost for UFAD C is due to increased cost of dampers and plenum dividers.

Overall this study indicates that there is little cost difference between UFAD and OH for increasing private office space except for large private office ratios where there is an HVAC cost savings for UFAD. These results, when compared to the $3.50/gsf baseline premium of UFAD, indicate that on a whole building level private office dominated buildings come closer to cost parity with OH systems than open office dominated buildings.

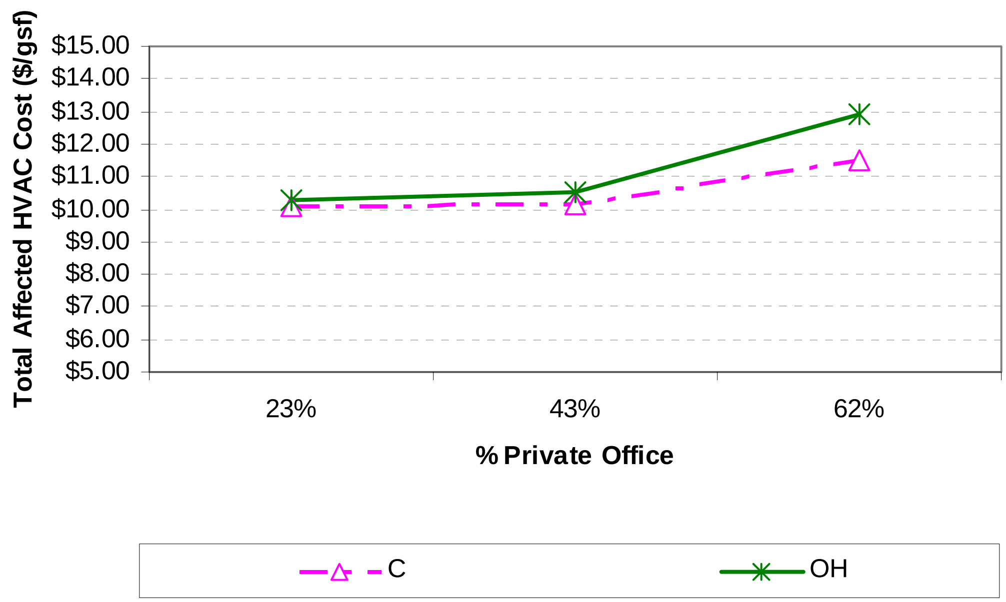

Figure 30. Equal Zoning: Total HVAC Cost Trend

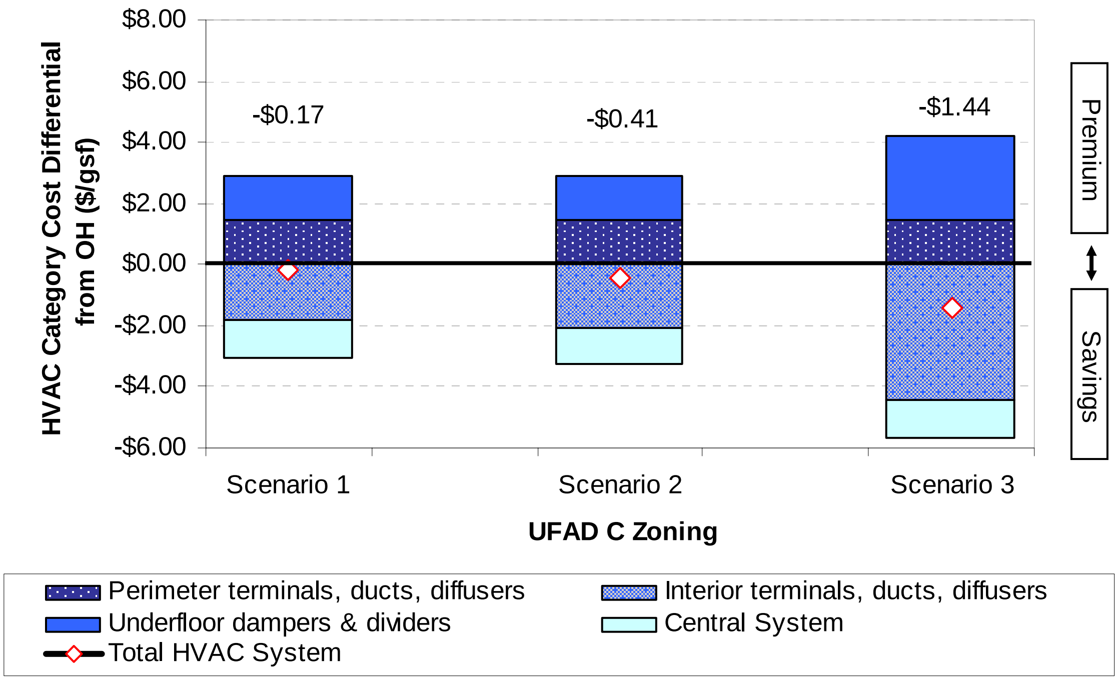

Figure 31. Equal Zoning: HVAC Category Cost Breakdown Differential

5.2.8 INTERNAL LOADS: AIRFLOW

Until a more detailed design tool is available for UFAD systems, current recommended practice is to assume the same design airflow for the UFAD system as would have been used for an OH system dealing with the same space and the same loads. In this study we tested the sensitivity of cost to UFAD design cooling airflow relative to OH design cooling airflow. The baseline assumption for the first cost model is to set the UFAD design airflow equal to that of the OH system. In this study we tested seven different flow rates all calculated in relation to the overhead flow rate.

Figure 32 shows the trend in total HVAC cost differences between UFAD systems and the OH baseline (that remains unchanged in this study). As expected, lower design airflows for the UFAD systems resulted in cost savings for the HVAC affected element of UFAD over the traditional overhead system. As UFAD airflow increases relative to OH, the opposite occurs. HVAC costs for UFAD A increase relative to overhead at approximately 12% less airflow than OH, while for the other UFAD systems HVAC costs are greater than OH in the range of 2% to 10% more airflow than OH.

Figure 33 shows a detailed breakdown of the HVAC cost components for this study. From this graph we see that the perimeter terminals, ducts and diffusers are the most significant contributor to this rise in cost.

Similar to results shown elsewhere in this report, the potential savings of $1-$3/gsf for reductions in airflow as large as 30% does not eliminate the overall building level premium for UFAD of $3.50/gsf for the baseline configuration, but does bring it close in some cases such as UFAD B and C.

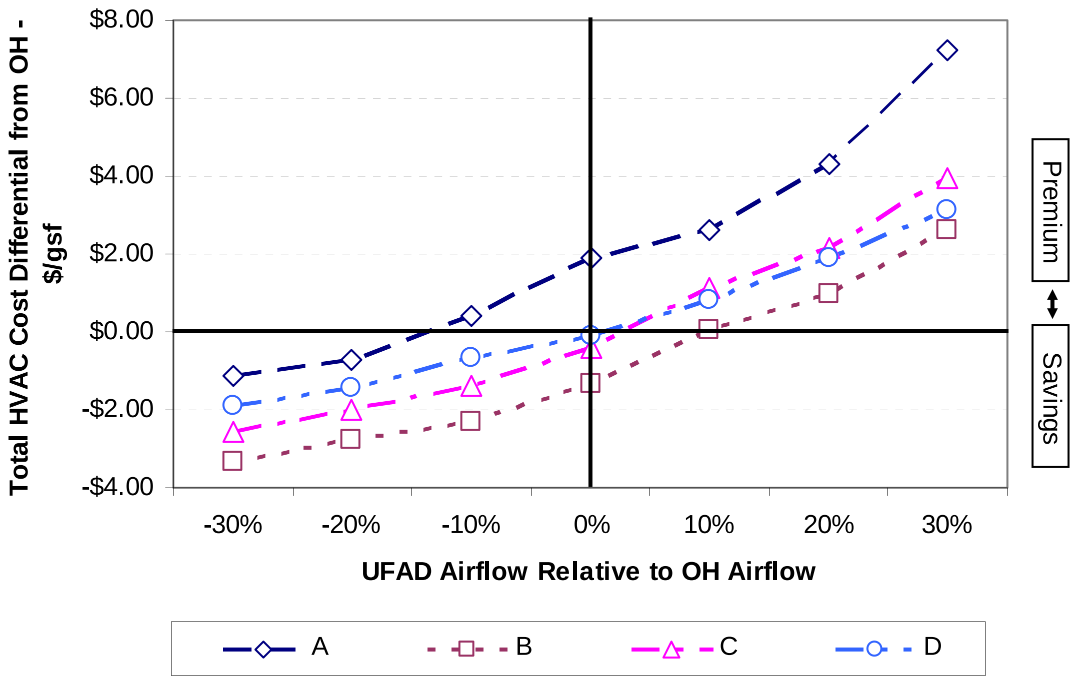

Figure 32. Airflow: Total HVAC Cost Differential Trend

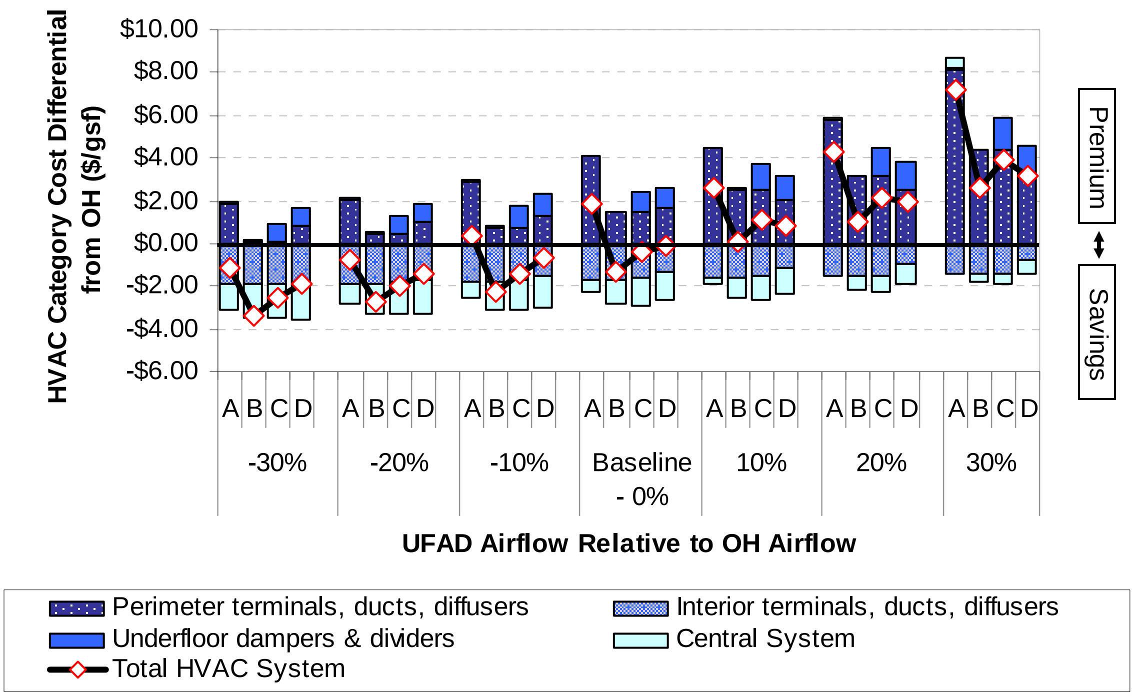

Figure 33. Airflow: Total HVAC Cost Differential Breakdown

5.2.9 PERIMETER: OH SYSTEM QUALITY

As the model is based on a cost differential and not absolute cost, we conducted some studies to test the sensitivity of the baseline overhead system. This study was done to see how the relative costs of UFAD would be affected by raising the baseline of the OH system using a higher quality VAV system.

The two variations in OH system quality that were compared were the baseline (Good) and a higher quality alternative (Better), as described below.

- **Good (Baseline):** Perimeter zones are modeled assuming reheat boxes where possible (i.e., unless energy codes dictate otherwise) and low-cost perforated diffusers. Interior open plan zones are sized as large as possible based on largest box sizes available. Reheat boxes are provided on interior closed spaces but interior open plan has zero minimums airflow settings (i.e., closed during heating and warm-up). The AHU is operated with economizer closed during the morning warm-up period when reheat boxes are used, warm-up is provided by reheat boxes (as opposed to a central heating coil). The AHU contains a preheat coil to prevent coil freezing.

- **Better:** We included this option to allow us to bracket the range of OH system designs from low/moderate quality/cost represented by the "good" option to high end quality/cost represented by the this "better" option. Many real systems are a mixture of these two so their cost is likely to be somewhere in between these two limits. Perimeter zones use parallel fan powered boxes (FPB) and high performance slot diffusers. Interior open plan zones are sized as large as possible based on largest box sizes available, have no reheat coils, and zero minimum airflow settings. Reheat boxes are provided on interior closed spaces. The AHU is off during the morning warm-up; FPBs provide heat by recirculation of room air that migrates to the interior zones.

The result of the Better OH alternative raises the OH HVAC costs by almost 100%. The increase in cost is due not only to the higher cost of parallel FPBs but also the high performance diffusers. Figure 34 compares the OH HVAC costs for the Good and Better alternatives. Note that the increase in OH HVAC costs for the Better alternative has a direct impact on the predicted cost differentials for all UFAD systems. In fact, as shown by the total height of the bars in Figure 35, this higher quality OH assumption eliminates the premium for all UFAD systems on a building-wide basis. These results indicate that the UFAD premium of our default baseline case could be heavily influenced by the OH configuration that is used for comparison.

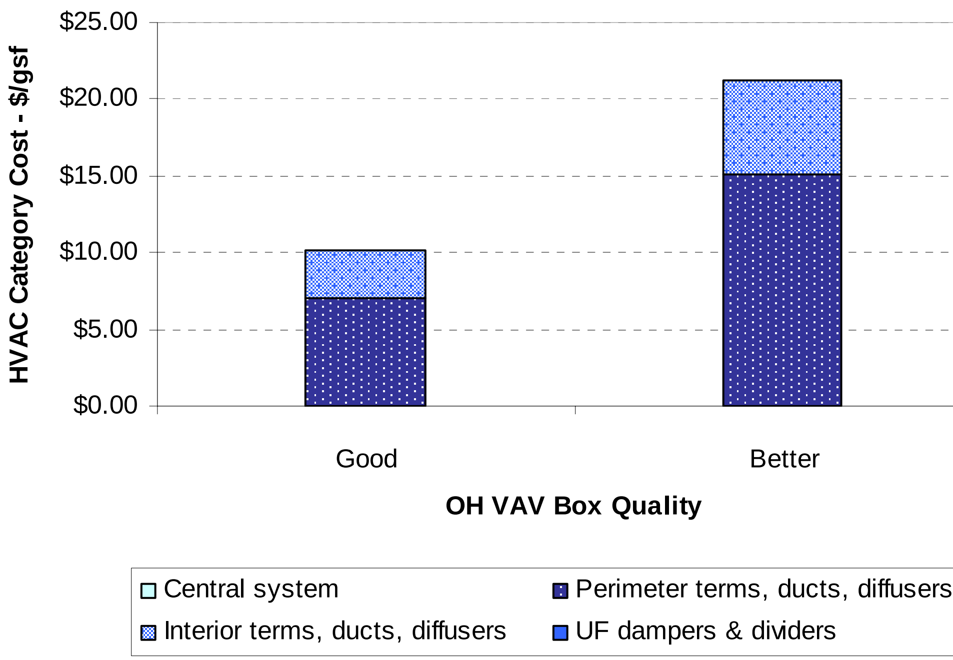

Figure 34. OH VAV Box Quality: HVAC Category Cost Breakdown

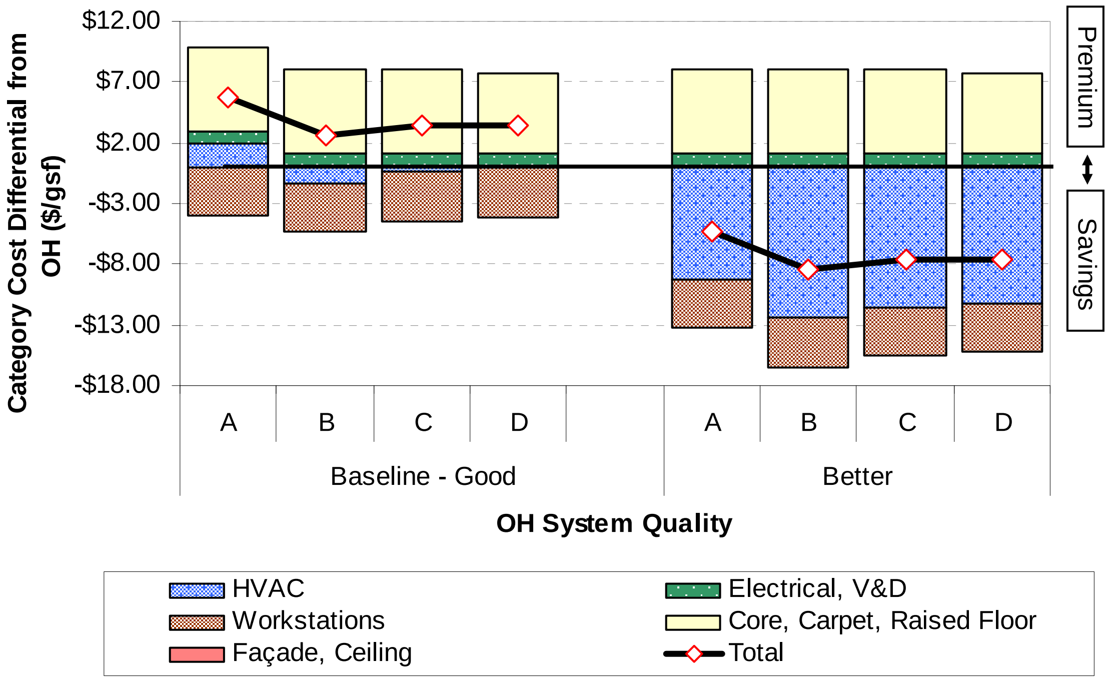

Figure 35. OH VAV Box Quality: Total Category Cost Differential Breakdown

5.2.10 PERIMETER: DUCTED RETURNS IN PERIMETER UFAD

We constructed the model such that the user may opt to allow a ducted return on perimeter fan terminal units to use air from the occupied space instead of plenum air as a first stage of heating operation in UFAD systems B, C and D. We assume in our baseline set of assumptions that UFAD D uses this option since this is predominately how these systems are installed in practice whereas UFAD B and C do not.[4] We used this study to understand the cost impacts of choosing this design option. It should be noted that the costs for UFAD A do not change in this study since the baseline assumption for these systems is to use ducted returns.

Figure 36 compares the total HVAC cost differential for the two cases studied: with and without the ducted return for perimeter UFAD. In this graph when the ducted return is included, it is shown that about $2/gsf is added to total HVAC costs for both UFAD B and UFAD C, whereas UFAD D experiences a change in cost differential of less than $0.20 /gsf when the return option is eliminated.

[4] This difference between the two system types should result in changes in life cycle costs due to energy use differences.

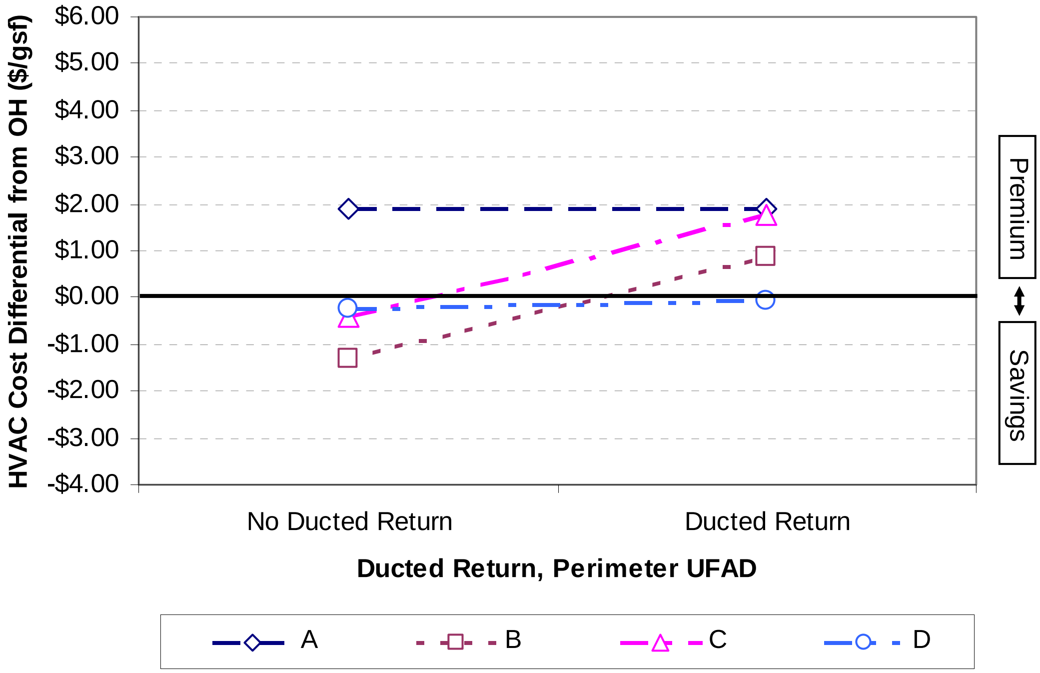

Figure 36. Ducted Return in Perimeter UFAD: Total HVAC Cost Differential Trend

5.3 INTEGRATED SCENARIO

Our intention with the first cost model is not only to be able to study the sensitivity of individual factors but also to be able to use the model to begin to investigate how certain combinations of strategies may create a more cost effective set of design options. In this study, we combined changes in ceiling type, wall height savings, perimeter airflow, and wiring to understand how one specific combination of elements may act together to create a more optimal configuration with respect to cost.

The scenarios tested were:

- Baseline – Steel building, Standard Baseline Assumptions (Appendix A)
- Scenario 1 – Steel building, perimeter UFAD airflow 25% less than OH baseline
- Scenario 2 – Steel building, perimeter UFAD airflow 25% less than OH baseline, modular wiring, materials provided by raised floor provider
- Scenario 3 – Concrete building, UFAD has an exposed ceiling (2’ height savings over OH baseline), perimeter UFAD airflow 25% less than OH baseline
- Scenario 4 – Concrete building, UFAD has an exposed ceiling (2’ height savings over OH baseline), perimeter UFAD airflow 25% less than OH baseline, modular wiring, materials provided by raised floor provider

Figure 37 presents the category cost differentials for the baseline and four integrated scenarios, and Table 12 lists the exact values for these differentials. We see that scenarios 1-4 lead to progressively lower costs for the UFAD configurations in comparison to the baseline. In particular, when a concrete building with an exposed ceiling is used (Scenarios 3 and 4), all four UFAD buildings are less expensive than the OH baseline. We also see that there are applications where a concrete building with 25% lower airflow than a conventional overhead system, modular wiring and a wall height savings of 2 feet can be cheaper than other scenarios using a steel structure, or higher airflow.

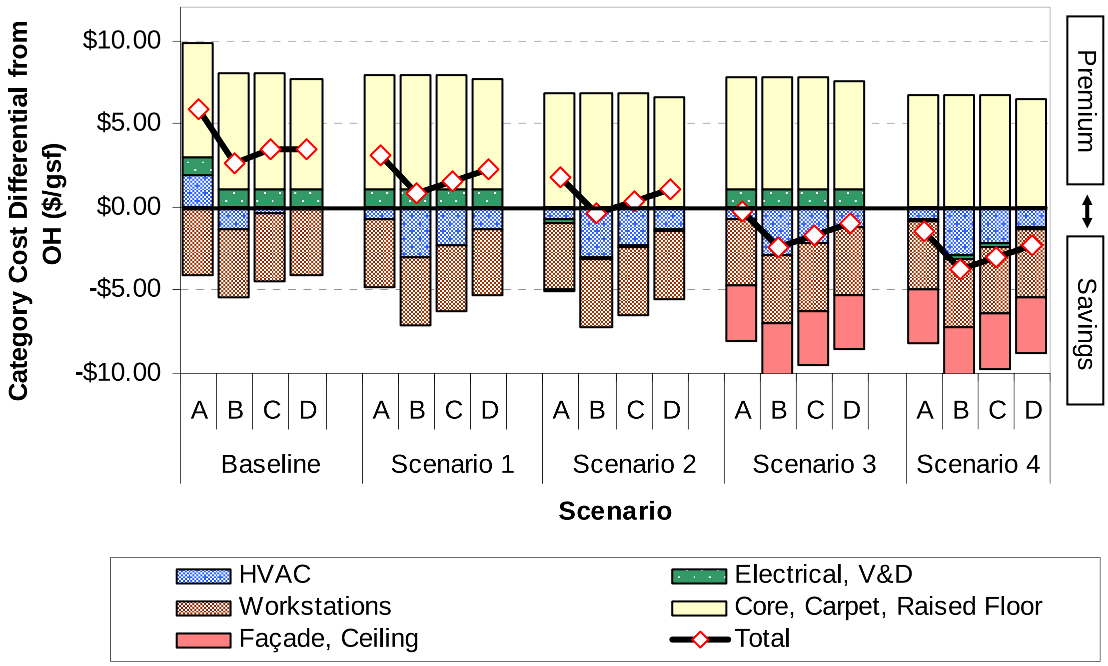

Figure 37. Integrated Scenario: Total Category Cost Differential Breakdown

Table 12. Integrated Scenario: Total Category Cost Differentials from OH ($/gsf)

	A	B	C	D
Baseline	$5.82	$2.60	$3.50	$3.49
Scenario 1	$3.07	$0.83	$1.58	$2.28
Scenario 2	$1.79	-$0.44	$0.31	$1.00
Scenario 3	-$0.23	-$2.47	-$1.72	-$1.01
Scenario 4	-$1.50	-$3.74	-$2.99	-$2.28

6 SUMMARY AND CONCLUSIONS

6.1 BUILDING GEOMETRY AND INTERIORS

Figure 38 and Figure 39 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 13 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.

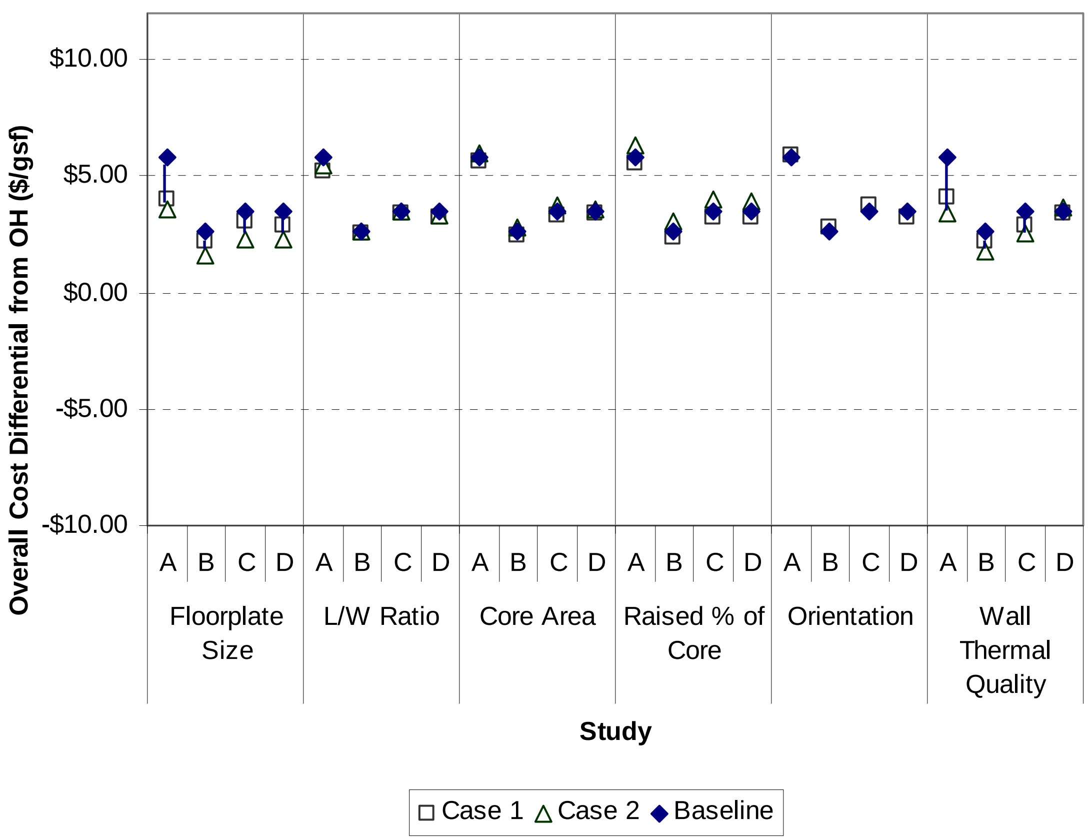

Figure 38. Building Geometry and Interiors, Group 1: Differential Sensitivity Summary

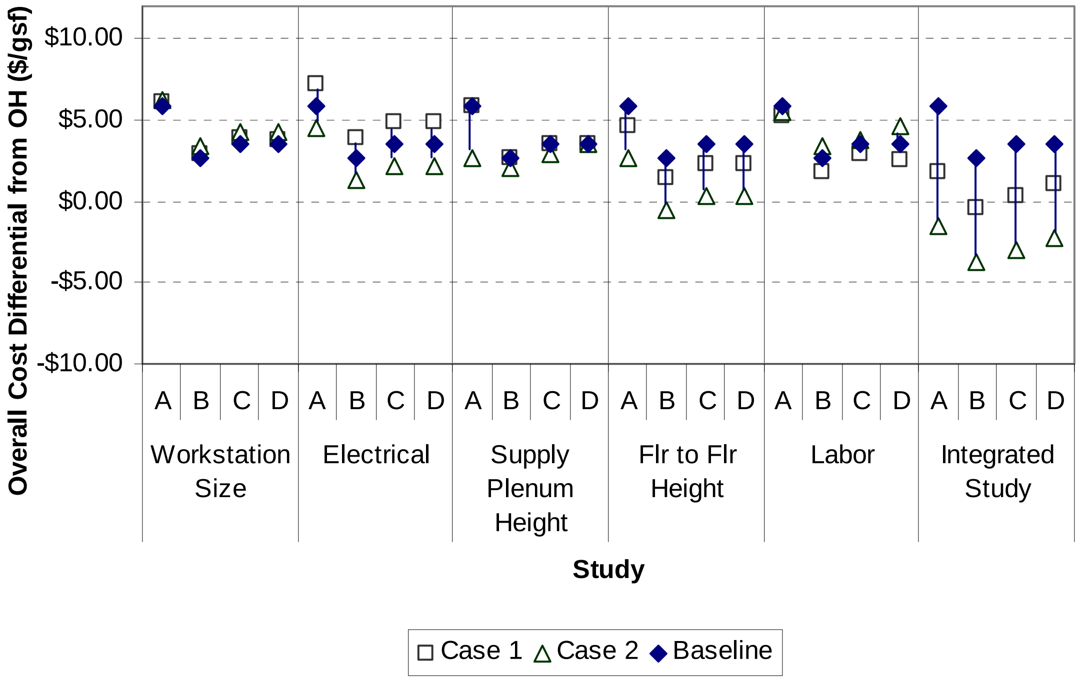

Figure 39. Building Geometry and Interiors, Group 2: Differential Sensitivity Summary

Table 13. 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 40 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 14. Based on these studies, the following key conclusions can be made:

- The percent of private office (Zoning: Private Office Area) 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 41 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 14. 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.

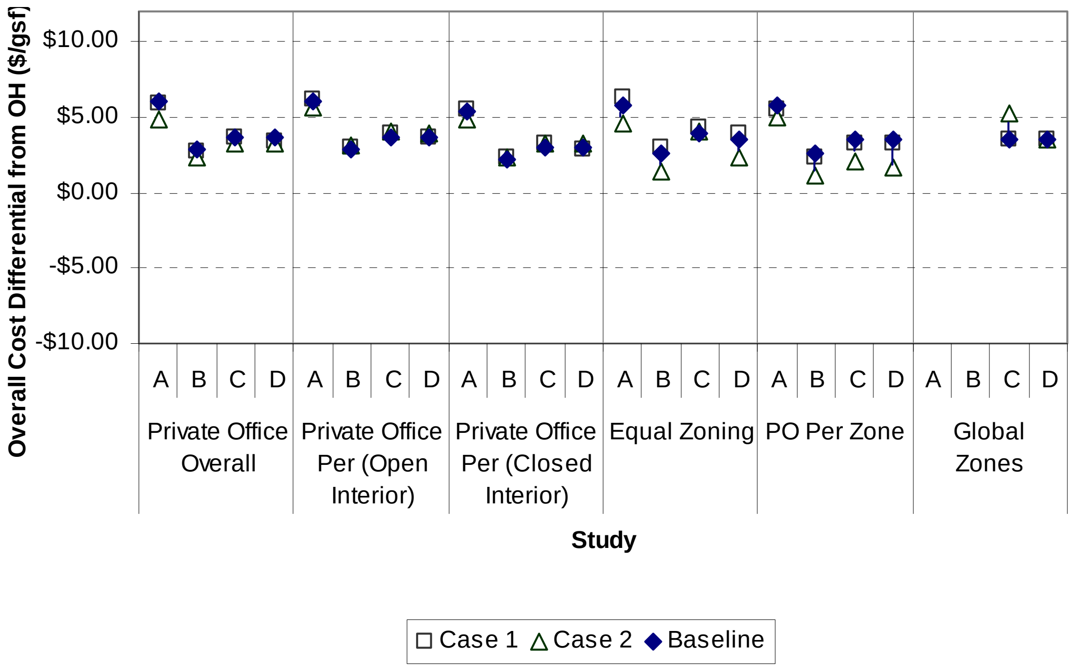

Figure 40. HVAC - Private Office and Zoning: Differential Sensitivity Summary

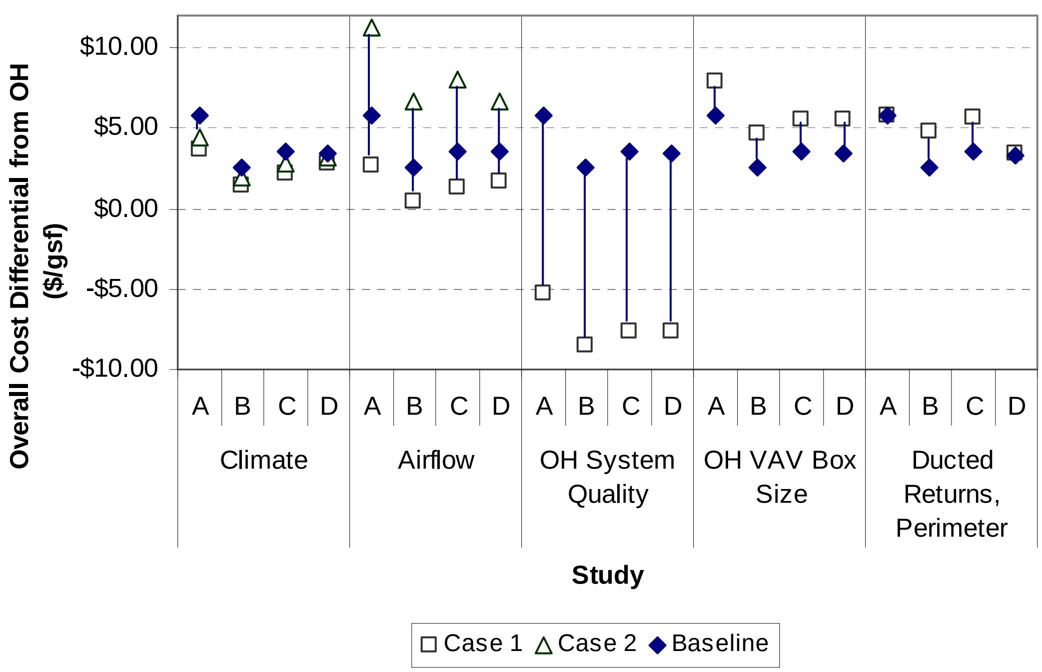

Figure 41. HVAC - Overall Factors: Differential Sensitivity Summary

Table 14. 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

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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.

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APPENDIX A: BASELINE DESIGN INPUTS

General Model Assumptions		UFAD	OH (Baseline)
Labor Profit and Overhead %:	O&P _sub	O&P_Tot W/ GC	
Electrical	15%	21%	21%
HVAC	15%	21%	21%
Access Flooring	10%	16%	16%
Raised core	15%	21%	21%
Furniture	15%	15%	15%
Carpeting	15%	15%	15%
Ceiling	15%	21%	21%
Sales taxes		10.00%	10.00%

Building Information	UFAD	OH (Baseline)
Location (Labor index city)	San Francisco - CA	San Francisco - CA
Climate	San Francisco	San Francisco
Materials Index	111%	111%
Installation Index	139%	139%
Orientation (direction of long axis, or facing of short sides)	East/West	East/West
Structure	Steel	Steel
Occupancy	Owner Occupied	Owner Occupied
Ownership	Single Tenant	Single Tenant

Building Layout and Dimensions	Units	UFAD	OH (Baseline)
Number of floors		10	10
Floor-to-floor height potential saving for UFAD systems	*feet*	0.0	NA
% of height potential saving want to capture	*%*	100.00%	NA
Actually Floor-to-floor height of wall	*feet*	12.67	12.67
Minimum Floor-to-floor height of wall	*feet*	12.67	12.67
Thickness of slab	*Inches*	6	6
Height of return air (RA) plenum **[0 if exposed ceiling]**	*feet*	2.0	3.17
Effective Floor to Ceiling Height	*feet*	9.0	9.0
Height of supply air (SA) plenum	*Inches*	14	NA
Building Type		High Rise	High Rise
Average area of Private office (PO)	*sq. feet*	150	150
Average area of Conference room (CONF)	*sq. feet*	250	250
Average ratio of Length to Width for CONF		1.5	1.5
Floor plate area allocation:			
Gross Floor Plate Area	*sq. feet*	20,000	20,000
Ratio of Length to Width		1.5	1.5
Floor Plate Length		173	173
Floor Plate Width		115	115
Perimeter Depth	*feet*	15	15
Total area - gross perimeter		7,760	7,760
Total area - gross interior		12,240	12,240

Total area - Net interior (tenant space)		11,016	11,016
Area allocation for floors other than the first (typical floor):			
Core - % of the total floor plate area	%	**10.0%**	10.0%
- % of the core area that is raised core	%	**50%**	NA
Perimeter:			
Number PO, long - Combined total, two **long** sides		**8**	8
Upper Limitation		28	
Number PO, short - Combined total, two **short** sides		**4**	4
Upper Limitation		16	
Total Perimeter PO		12	
Number CONF, long - Combined total, two **long** sides		**2**	2
Upper Limitation		14	
Number CONF, short - Combined total two **short** sides		**2**	2
Upper Limitation		9	
Total Perimeter CONF		4	
% Perimeter area dedicated to PO	%	23.2%	23.2%
% Perimeter area dedicated to CONF	%	12.9%	12.9%
% Perimeter area dedicated to open plan (OPN)	%	63.9%	63.9%
Interior (UFAD conditioned tenant space)			
Number PO - Interior		**10**	10
Number CONF - Interior		**4**	4
% Interior area dedicated to PO	%	19.3%	19.3%
% Interior area dedicated to CONF	%	9.1%	9.1%
% Interior area dedicated to OPN	%	71.6%	
Area allocation for the first floor:			
% of floorplate area dedicated to Lobby		**20%**	20.0%
% of floorplate area dedicated to the core		10.0%	10.0%
% of floorplate area dedicated to office space		70%	70%
Conditioning method for private offices in the first floor		**UFAD**	OH

Workstations Layout and Dimensions	Units	UFAD	OH (Baseline)
Workstation size (length and width)	*feet*	**8.0**	8
Base size of workstation	*sq. feet*	64	64
Number of workstations per cluster		**6**	6
Corridor Size	*feet*	**4**	
Cluster adjacent area	*sq. feet*	560.00	560.00

Number of workstation clusters	21.00	21.00
Number of workstations - Interior	72.00	72.00
Number of workstations - Perimeter	53.00	53.00

Ceiling Treatments	UFAD	OH (Baseline)
Ceiling Type (See RA plenum height)	Hung Ceiling	Hung Ceiling
Ceiling quality	Good	**Good**
Labor rate - carpenter	$76.74	$76.74
Ceiling Painted Areas	None	None
Labor rate - painters, ordinary	$68.30	$68.30
Lightning	Standard Lights	Standard Lights
Fixture type (Pendent mounted is the only option for the Exposed Ceiling)	**Recess mounted in grid**	**Recess mounted in grid**
Labor rate - Electrician	$98.44	$98.44
Acoustical Treatment	None	None
Labor rate	$84.56	$84.56
Fire Proofing	None	None
Labor rate	$84.56	$84.56
Fire Sprinklers	Hung Ceiling	Hung Ceiling
Sprinklers in the underfloor?	**No**	NA
Labor rate	$90.92	$90.92

HVAC Parameters	Units	UFAD	OH (Baseline)
Perimeter Loads - Wall Selection		**Good**	Good
Number of Private Offices per Zone		**5**	5
Number of zones in the Interior **(only for UFAD C and D)**		**1**	
Conference room occupancy - area per person	*sq. feet*	**10**	
Average occupancy load in conference rooms	*# people*	25	25
Perimeter diffuser option for UFAD A, B and C systems		**Bar grille**	NA
OH perimeter system VAV terminal type		NA	**Good - reheat plus FPB**
Limit OH Terminals to 1,500 CFM?			**Yes**
Ducted return from space for heating in VAV UFAD systems (UFAD_B and _C)?		No	**NA**
Ducted return from space for heating in York systems (UFAD_ D)?		Yes	**NA**
Plenum Supply Ducting		Yes	**NA**
Leak Detection?		Yes	**NA**
Load factors, perimeter zones:			
K (load offset multiplier)		**1.00**	1.00
DEL-T_CLG (overall SAT - RAT difference)	*°F*	**14.08**	**15.00**
DEL-T_HTG	*°F*	**45.00**	**20.00**
Internal loads:			
Airflow per square foot for internal loads in OPN and PO - Interior		**0.85**	0.86

Overhead lighting input (gross input), private office	*W/sf*	1.20	1.20
Overhead lighting input (gross input), conference room	*W/sf*	1.50	1.50
Overhead lighting input (gross input), open plan	*W/sf*	1.20	1.20
Ratio of overhead light heat to space - PO & Open Space	*%*	**80%**	80%
Ratio of overhead light heat to space - Conf	*%*	**80%**	80%
Small power internal gains, private office	*W/sf*	2.00	2.00
Small power internal gains, conference room	*W/sf*	2.50	2.50
Small power internal gains, open plan	*W/sf*	2.00	2.00
Diversity factors:			
Perimeter (for UFAD_ B, _C, _D and OH)		**0.65**	0.65
Interior (for UFAD_C, _D and OH)		**0.80**	0.80
Labor rate, HVAC installation		$87.94	87.94

Access Floor	Units	UFAD	OH (Baseline)
Access floor in OH systems		N/A	No
Vendor		Tate Access Floors	N/A
Office usage (Loading)		Medium	N/A
Labor, Access floor installation		$66.39	$66.39
Tile Side Length	*Feet*	2.00	N/A

Electrical/Voice and data	Units	UFAD	OH (Baseline)
Workstation electrification type		Conventional (MC)	Power Pole
Furniture Type		Non-Powered	Powered
Powered furniture type (only when powered selected)	**N/A**	Basic powered	Basic powered
Modular wiring provider for electrical material/Installation		Contractor provides both	N/A
Provider of material		Contractor	N/A
Provider of electrical installation		Contractor	N/A
Labor rate savings for installation by access floor vendor		30%	N/A
Private Office electrification [*default = PVD*]		PVD	Wall Mount
Labor rate, electrical		$98.44	$98.44
Number of voice cables per WS		1	1
Type of voice cable		Cat 5	Cat 5
Number of data cables per WS		1	1
Type of data cable		Cat 5	Cat 5
Cable tray?		No	Yes
Labor rate, voice and data		$52.50	$52.50

Façade	Units	UFAD	OH (Baseline)
Façade Quality		**Better**	
Column Spacing	*Feet*	**40.00**	40

Carpeting	Units	UFAD	OH (Baseline)
Carpet selection		Carpet tile - 18x18	Carpet tile - 18x18
Churn		44%	44%
Waste per churn	*sq yds*	1	1
Usable life		15	15
Attic stock		3%	3%
Labor rate, carpet baseline		$68.61	$68.61

Reference labor rates - Baseline: San Francisco	Affected area	Cost method	Units	Adjusted rate incl. GC profit San Francisco - CA
Carpenter	Ceiling Treatment	Unit Labor	*US$/Hr*	**$76.74**
Painter, Ordinary	Ceiling Treatment	Unit Labor	*US$/Hr*	**$68.30**
Acoustical treatment	Ceiling Treatment	Unit Labor	*US$/Hr*	**$84.56**
Fire Proofing	Ceiling Treatment	Unit Labor	*US$/Hr*	**$84.56**
Sprinklers	Ceiling Treatment	Unit Labor	*US$/Hr*	**$90.92**
Crew for electrical installation	Electrical	Detailed	*US$/Hr*	**$98.44**
Crew for voice and data installation	Voice and Data	Detailed	*US$/Hr*	**$52.50**
Crew for carpet	Carpet	Unit Labor	*US$/Hr*	**$68.61**
Crew for HVAC	HVAC	Detailed	*US$/Hr*	**$87.94**
Furniture assemble and installation (Powered)	Workstations	Detailed	*US$/WS*	**$372.40**
Furniture assemble and installation (Non-Powered)	Workstations	Detailed	*US$/WS*	**$310.41**
Working Foreman (Access Floor)	Access floor	Detailed	*US$/Hr*	**$88.30**
Installer (Access Floor)	Access floor	Detailed	*US$/Hr*	**$72.25**
Apprentice (Access Floor)	Access floor	Detailed	*US$/Hr*	**$56.19**