Integrated cost estimation methodology to support high-performance building design

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Abstract

Design teams evaluating the performance of energy conservation measures (ECMs) calculate energy savings rigorously with established modelling protocols, accounting for the interaction between various measures. However, incremental cost calculations do not have a similar rigor. Often there is no recognition of cost reductions with integrated design, nor is there assessment of cost interactions amongst measures. This lack of rigor feeds the notion that high-performance buildings cost more, creating a barrier for design teams pursuing aggressive high-performance outcomes.

This study proposes an alternative integrated methodology to arrive at a lower perceived incremental cost for improved energy performance. The methodology is based on the use of energy simulations as means towards integrated design and cost estimation. Various points along the spectrum of integration are identified and characterized by the amount of design effort invested, the scheduling of effort, and relative energy performance of the resultant design. It includes a study of the interactions between building system parameters as they relate to capital costs. Several cost interactions amongst energy measures are found to be significant.

The value of this approach is demonstrated with alternatives in a case study that shows the differences between perceived costs for energy measures along various points on the integration spectrum. These alternatives show design tradeoffs and identify how decisions would have been different with a standard costing approach. Areas of further research to make the methodology more robust are identified. Policy measures to encourage the integrated approach and reduce the barriers towards improved energy performance are discussed.

Introduction

Design teams evaluating energy conservation measures repeatedly face the hurdle of increased capital costs. These measures are now widely seen as attractive long-term investments with lower lifecycle costs, but the lack of immediate funds in the construction budget creates a significant barrier for implementation. Current methods of sequential design and cost estimation make it harder to follow an integrated approach that would change the perception of these capital costs. Isolated examples of integrated design in the sustainable design community have demonstrated that, with adequate design, analysis, and cost estimating effort, it is possible to achieve high performance without significantly increasing the cost beyond a standard performance design. However, without a clearly defined alternative methodology, such experiences remain few in number and inaccessible to the larger market where design teams approach energy-efficient design based on anecdotes available in the industry.

This study tackles the capital cost barrier by outlining an integrated cost methodology to move design teams from a simple awareness of the value of energy efficiency measures to enable them to take action on their building projects. The theoretical framework shows a spectrum of integration. Various points of integration along the spectrum can be achieved based on the amount of design effort invested and the scheduling of this effort. As teams gain more experience with integrated design, they can move higher up the integration spectrum. This methodology includes a study of the interactions between building system parameters as they relate to capital costs. Several cost interactions amongst energy measures are found to be significant. The Assembly and Systems Method is identified as the cost estimation method ideally suited for integrated costing. Example cost-size functions for HVAC systems, based on data from assembly cost guides, are presented. These functions need further study towards developing a robust methodology for integrated cost estimating tools.

An example office building is used to study the varying levels of cost integration. The case study demonstrates that different cost information can be presented for the same set of energy efficiency measures, depending on whether shared equipment and system downsizing are taken into account. An owner's decision to incorporate energy efficiency is dependent on the perceived costs, and this ultimately affects the level of energy efficiency achieved.

This study currently bases the methodology on experiences gained on medium sized commercial buildings such as offices and schools in the U.S.A. Further work will be needed to make the methodology apply more broadly and robustly enough for other building types and sizes and to allow integration with non-energy sustainable design measures such as water conservation technologies.

Several policies can encourage the practice of integrated design and cost estimation to reduce the perceived first cost barrier: 1) similar to the requirements for lifecycle costing by some government organizations and public agencies, integrated costing could also be required to assure that capital cost savings are accounted for in integrated design; 2) public agencies can lead the market by changing the design fee structures to recognize greater importance of early design consideration of cost integration. Design fees should be decoupled from capital cost expenditure for equipment; 3) utility rebates and tax deduction programs can also encourage integrated design of building systems by providing high incentives to the designers for overall building energy performance. These design incentives should be decoupled from reported incremental costs; 4) provide funding support to develop publicly available cost databases and costing functions for system or assembly cost estimation; and 5) develop best practice case studies that show how design teams save owners' money through integrated designs.

Background

Market barriers most frequently referred to by demand side management (DSM) representatives, such as program managers and practitioners, are lack of information of energy-efficient products and practices, high first costs, uncertainty and risk regarding the performance of the technologies, and lack of incentives to pursue energy efficiency in the current economic frameworks. Eto et. al. (1996) found that DSM representatives considered high first cost as the single most important barrier. DSM programs, and more recently federal and local legislation, routinely address this barrier by reducing first costs through rebates, tax incentives and other forms of financial assistance (Eto et. al.,1996). These incentives are generally structured such that the first cost is never completely eliminated and that the consumer is expected to bear some portion of the increased cost.

Commercial building projects typically work with a predefined and generally fixed construction budget. Against the spectre of unpredictably rising costs of construction, even a small increase in the first cost makes energy-efficient technologies appear out of reach. Thus efficiency options are often eliminated at the face value of the higher cost (Kats et al., 2003). In recent years, the reduced lifecycle costs due to these technologies have made them an attractive investment option; however with the typical fixed construction budget, the ability of a design and construction team to invest in these technologies continues to be severely limited. In the sustainable design industry, *whole building*, or *integrated*, design is regarded as a way of achieving high performance without significantly raising the first cost of the building beyond a standard performance building. However, this process is also seen as the most difficult aspect of green building design (Market Transformation to Sustainability, 2006).

The primary barriers to an integrated design process are as follows.

Unfamiliarity with the process: The "business as usual" approach to design is a sequential solving of design issues. Integrated design requires a simultaneous resolution of multiple issues by multiple experts. The lack of a clear map of an integrated design process means that design teams easily fall back to conventional linear practice.

Owners' expectations: Owners and users have an "as usual" expectation about the outcome in terms of aesthetics and functionality of the building or system. An integrated design process necessitates that all the stakeholders, including the owner, have an open mind towards new technologies.

Perception of risk by the engineers: The integrated process involves going beyond rules of thumb and abandoning traditional safety factors and margins. This requires increased trust between different design disciplines and a continuous check through the design and construction process such that fine-tuned design parameters are not violated. Since the integrated design is interdependent on a mix of parameters, a small change in one can have a cascading or "domino" effect on others. Many designers do not feel a sense of comfort with these narrower margins for error.

Fee structures: A simultaneous design process requires each designer to develop and assess multiple alternatives early in the process. This requires more design effort overall and especially during Schematic Design. As shown in *Figure 1*,[1] design fees are typically structured assuming a smaller effort in the early design phases with greater effort in the later phases. This apportioning of fees is not well-suited to integrated design. Furthermore, fees are currently structured assuming a linear design process with more fees for architects during Schematic Design and less fees for the engineering disciplines. It assumes that engineers will not be involved until after the architectural design has been conceptualized. An integrated process requires a more intense Schematic Design effort from the engineering disciplines that is not accounted for in the current fee schedules. The advent of design based on Building Information Modeling (BIM) is likely to change this in the future, since BIM will require more

1. The break-down of fees shown here are typical in the U.S.A and based on professional experience of the sources cited as well as from purchasing guidelines by the State of Washington, U.S.A.

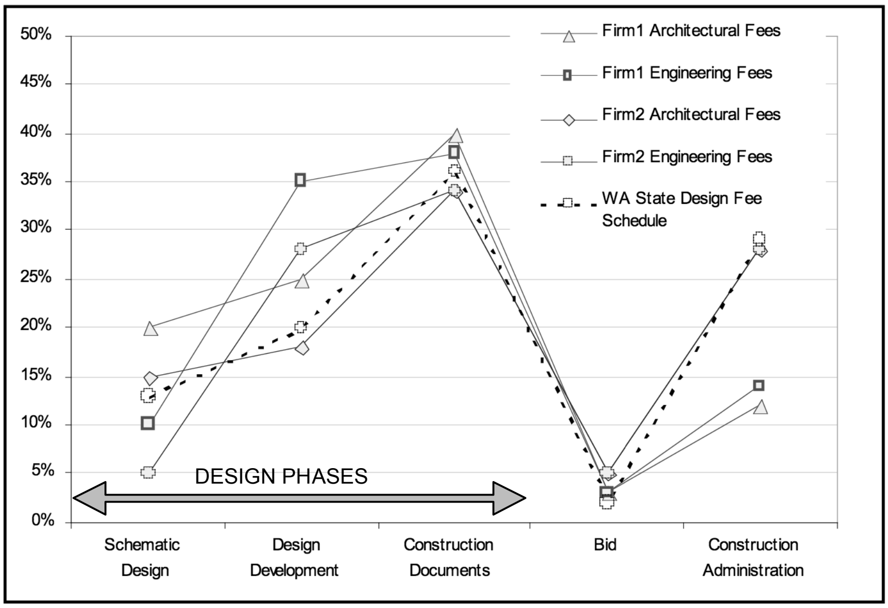


Figure 1. Fee structures for architectural and engineering firms throughout the design and construction process (Flynn, 2006, Gouveia, 2006, OFM-WA, 2006)

development of design early in the process with less effort required for documentation and coordination in the Construction Documents phase (Davis, 2007).

ABSENCE OF INTEGRATED COST ESTIMATION

If one of the objectives of an integrated design process is to reduce the first cost barrier, an explicit and related methodology for cost estimation is needed. Literature review and survey of the market reveals a lack of a specific methodology for integrated cost estimation. The "Whole Building Design Guide" (NIBS, 2007) focuses heavily on energy performance and related tools but does not adequately address the first cost issue. A review of *Estimating Today*, a monthly publication by the American Society of Professional Estimators shows that cost estimation for high-performance buildings is generally perceived by cost estimators as a series of added cost items. Kutilek (2005) notes that certain items in LEED can decrease costs but they would not be the norm; thus the author recommends a process of identifying items that would have "no," "minor" and "major" added cost implications. According to Sheffer (2006), typical cost estimates are a series of line items that are simply included or removed in isolation and not as grouped solutions where line items are interdependent. Similarly, typical "value engineering" methods consider building elements as independent. Unless they are inextricably linked, "value engineering" assumes that elements can be individually removed without significant impacts on other components—an assumption that may be false.

A survey of the market, however, does reveal isolated instances of varying levels of successful cost integration methods. Schaffner (2006) described an integrated analysis for a building at MIT in Cambridge, Massachusetts (U.S.A.) where a prototypical 200 m^2 floor was developed by all design disciplines and evaluated in detail for performance and first costs. Selecting a small prototypical portion of the building allowed the team to focus on system integration where the performance results and costs could be extrapolated to the entire building subsequently. For the Cambria Office Building in Ebensburg, Pennsylvania, (U.S.A.) (Deru, 2005 and Schaeffer, 2006), the design team had built trust with each other during a previous building project. The team was thus able to use an integrated design process to target downsizing, eliminate systems components, and minimize redundancies, while improving performance and reducing energy consumption. The team developed integrated solutions as alternatives through energy modelling, alternative load calculations and interdependent cost estimates. For the College of Public Health in Iowa City, Iowa (U.S.A), Reed (2006) used Uniformat, a Construction Specifications Institute (CSI) standardized elemental classification structure that is comprehensive across all building systems and provides quantity parameters for these systems or components. This format was familiar to the professional estimators on the project. Using the Uniformat list, Reed (2006) then evaluated high-performance alternatives, by identifying every building component that would be affected by each alternative. While tedious, this process has a high potential for cost integration.

OBJECTIVES

This study has the following objectives:

1. Develop a framework for integrated design and integrated cost estimation for building systems. Such a framework will have elements and methods that are more specific than the existing guides on integrated design and yet be general enough that they can be applied across building types or geographical regions where building design, construction and operation practices are similar.
2. Test the framework with a case study to learn if design and estimation methodologies that are more integrated will result in higher energy savings with lower first costs reported.

In the future, as the integrated design and cost estimation framework is used in real design projects, the following hypothesis can be tested: integrated approaches will result in owner decisions to implement higher levels of energy conservation in their buildings.

Methodology

In accordance with the *Whole Systems Integrated Design Process* document (Market Transformation to Sustainability, 2006), the following recommendations that apply to integrating costs are considered:

- Find opportunities that optimize the interdependence and syntheses between building systems
- Optimize costs, specifically first costs using construction costs relevant to the project
- Eliminate redundancies and streamline systems rigorously using a carefully considered method of analysis

Development of the methodology begins with a high-level mapping of the *spectrum* of cost integration. Here, the term "bundling" is used to refer to the grouping together of individual energy conservation measures. Bundling includes the concept of integration, but there are various levels of integration across the spectrum of ways to bundle energy conservation strategies.

The methodology is further developed by assessing the various design parameters, from window glazing to lighting controls, for cost *interactions*. The parameters are rated for the level of impact on the others, and the primary interactions are identified.

With greater understanding of the spectrum of cost integration and the levels of cost interaction amongst design parameters, a *spreadsheet tool* is developed that can be used to understand these factors for a given project. The tool is used to look at the cost implications of the bundling methodology as well as the energy conservation impact of various design parameters for a typical office building.

SPECTRUM OF COST INTEGRATION (BUNDLING)

Integration of design and first costs is expressed along a continuum that starts with the lowest levels, where almost no integration exists, and goes all the way to the highest levels of integration, where the need for a new building is eliminated.

No Bundling: At this level, individual ECMs have no impact on each other in terms of design implications or first cost. ECMs are included in the design simply based on their individual merit, possibly by including those that have a payback period less than a certain threshold value. A design team following this process could make decisions based on analysis of individual ECMs, savings and payback reported by equipment sellers, or the availability of utility component rebates.

Simple Bundling: A simple bundling process evaluates a group of ECMs as a combined solution. Instead of including individual ECMs based on their individual merit, this process evaluates the entire bundle of ECMs as a single alternative. A bundle could consist of ECMs that deal with building envelope, insulation, glazing, lighting, and mechanical controls, and a design team could evaluate multiple such bundles as alternative design solutions. Detailed energy analysis of individual ECMs, as well as the proposed bundles, is necessary to evaluate their energy performance. Bundling allows ECMs with short and long payback periods to be included in the design as long as the overall bundle payback is acceptable to the owner. However, evaluating the combined energy performance of a bundle does not provide sufficient information to a design team to enable accounting of the design and cost interactions of the ECMs, as they are still considered additions to a base design.

Optimized Bundling: The process of optimization evaluates implicit strategies as well as their alternatives using a parametric analysis for energy performance and costs. This method groups ECMs that are implicit in the design into a Design Base bundle. The implicit ECMs have no additional first cost beyond the building budget as assumed by the design team. Sometimes an ECM is included in a design based on past experience, where its energy efficiency value is either assumed or ignored. An example of this is where an architect provides windows for daylight; however without analysis, the overall window area is more than the optimized value for the building. Since this is implicit in the initial design, such ECMs are considered part of the design budget and thus are assumed to have no incremental cost. A design team will often enter a high-performance building design process with multiple such ECMs implicit in the design. Parametric modelling can evaluate the values of performance parameters both below and above those implicit in the design, thus bracketing the issue. A cost benefit analysis of all the performance parameter values can help remove implicit ECMs that have low value and include others that have a higher value by trading off their costs against each other. In the case of the excess window area example, it would be possible to reduce the window area to an optimized value and use the first cost released to implement additional ECMs with higher value, such as a higher efficiency cooling system. This process requires parametric modelling, definition of a zero cost Design Base and trade-offs between ECMs to achieve an overall optimized bundle of strategies. However, similar to Simple Bundling, Optimized Bundling does not necessitate the accounting of cost interactions between ECMs – each parameter is still estimated individually for its incremental cost.

Single Interaction Bundling: At this level of integration, an ECM's impact on the design of other building systems is accounted for in the cost estimates for energy efficiency. Examples include the impact of higher efficiency lighting on reduced cooling loads and cooling system capacity, increased surface reflectances that improve the efficacy of the lighting system thereby allowing a reduction in the overall number of lighting fixtures, and energy recovery wheels reducing the cooling and heating system capacities. The extent of the cost integration is such that one system affects only one other system. Cascading, or domino effects, of costs are not considered at this level.

Shared Equipment: Shared equipment is a type of interaction bundling that takes into account the common components between different ECMs, and this intersection of components is reflected in the cost estimation. Examples include occupancy and daylighting controls that share low voltage wiring and relay costs, and occupancy sensors that are used both for lighting controls and control temperature setbacks and airflow ventilation.

Multiple Interaction Bundling: This level of integration takes into account the domino effects of an ECM on multiple systems. For example, paint selection for improved interior

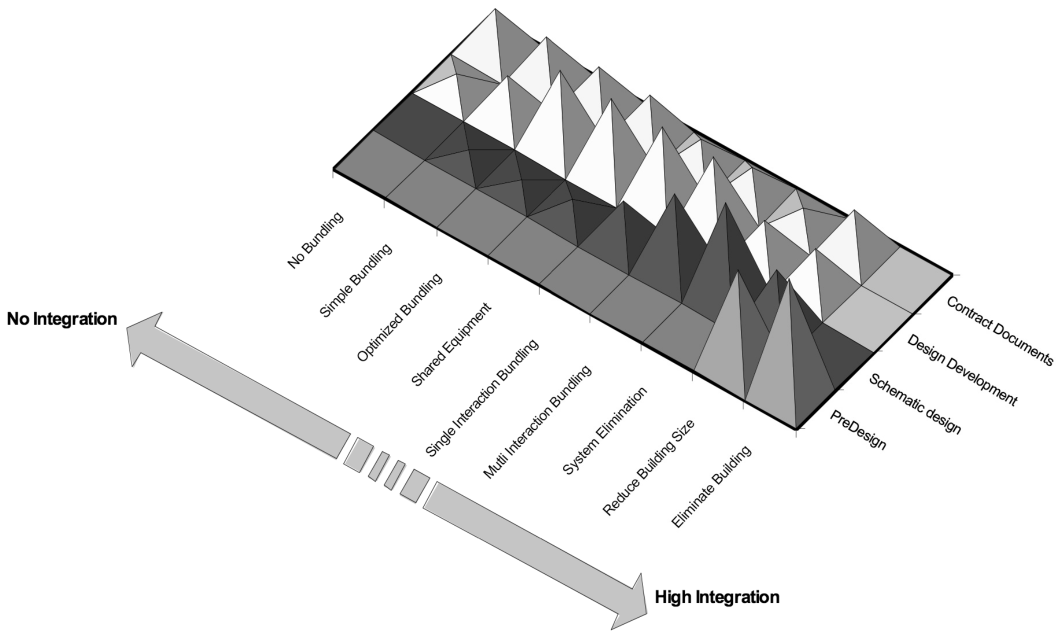


Figure 2. Conceptual range of relative design team effort for high performance decision making by design phase for the spectrum of integration (not to scale)

surface reflectances can impact lighting fixture count, which affects the dimming ballast count for daylighting control and the reduced capacity of cooling equipment. Domino effects of systems can also require iterative assessment of system costs. As another example, improved glazing visible transmittance can reduce window areas, which can reduce the cooling system loads with smaller HVAC ducts, which allows a higher ceiling height, which then allows the windows to be raised higher, which improves the daylighting performance, which further reduces the cooling capacity and duct sizes. Obviously, an exhaustive accounting of multiple interactions of building systems would be a very involved process that could be achieved with very sophisticated design and estimation tools or with a very committed design team effort.

System Elimination: This approach explores the improvement in the efficiency of one system to the extent that it allows the complete elimination of another system. For example, in certain climates the installation of 4-pane insulated glazing allows the elimination of the perimeter fin tube radiation. This was the approach taken for the headquarters of the Rocky Mountain Institute in Colorado (U.S.A.) where a passive solar design combined with a super insulated building envelope allowed the designers to eliminate the heating system in the building (Rocky Mountain Institute, 2006)[2].

Reduce Building Size: Shared spaces and assigning common physical spaces to multiple functions results in a reduced building program. For example, library rooms in offices can be used as conference spaces, and multipurpose rooms in schools can function as special classrooms needed for art or music education. This is one of the most effective ways of reducing costs and energy consumption in buildings, which can be achieved through rigorous programming exercises in the pre-design phase. This approach requires owner buy-in and commitment.

Eliminate Building: This is perhaps the best way of reducing the environmental impacts of building and avoiding the cost of new construction. For example, if a company expects a 10 % personnel growth that would require a building addition or building a new and larger facility, an alternative approach would be to institute a telecommuting program for 10 % of the employees such that the existing building area could continue to serve the increased company size. This avoids the cost and environmental impacts of new construction and avoids additional energy use, while also reducing the transportation energy and infrastructure related impacts of commuting.

Discussion

Different levels of integration are applicable to each project situation based on opportunities available, the owner's commitment, design team experience and mutual trust, design and construction scheduling, fees, owner's performance and cost expectations. The spectrum presented in *Figure 2* [3] may be used as a starting point for design teams undertaking integrated design to identify an appropriate level for their particular project. The following section provides more information on how performance and cost parameters relate to the levels of integration across the spectrum.

Figure 2 shows the relative design effort required at each design phase for various points along the integration spectrum. *No Bundling, Simple Bundling*, and *Optimized Bundling* have a design effort profile that is similar to that assumed in a standard fee format, although *Simple* and *Optimized Bundling* have an increased effort in Design Development due to the energy analysis needed. *Shared equipment*, *Single* and *Multi-Interaction Bundling* require significantly more effort in Schematic

2. The only heating provided for this building consists of two wood burning stoves that are used on the coldest winter days. Conventional heating that uses boilers and related piping was eliminated in the design.

3. Figures 2 and 3 are based on the authors' professional experience and research conducted through discussions with sources cited in this paper.

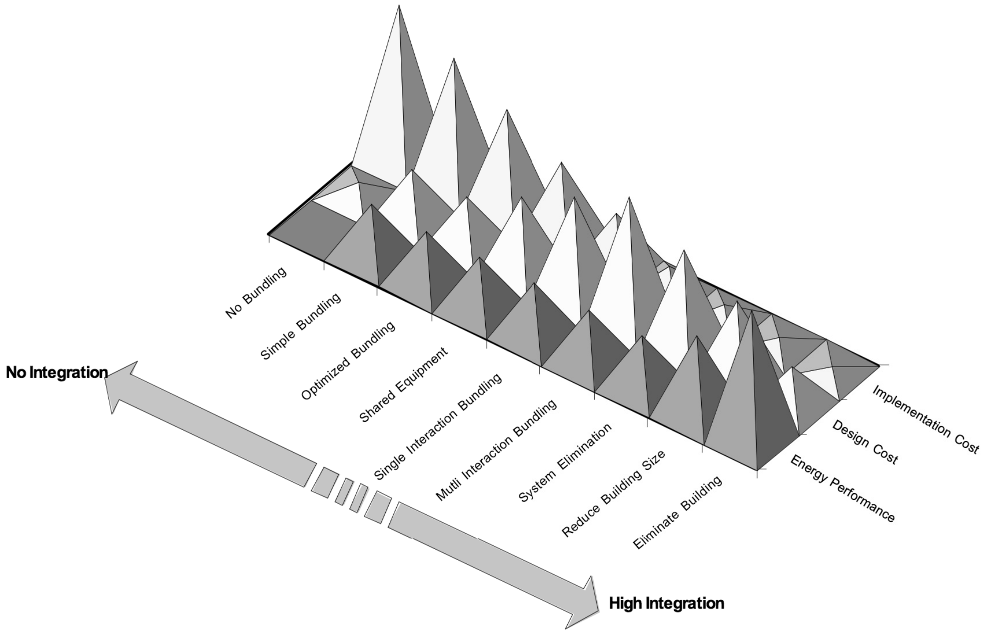


Figure 3. Conceptual range of relative cost for high-performance decision making and energy performance impacts for the spectrum of integration (not to scale)

Design and Design Development; and Schematic Design effort increases between these three levels along the integration spectrum. The two highest levels of integration, *Reduce Building Size* and *Eliminate Building,* require significant efforts during Pre-Design. In summary, it is apparent that traditional fee structures cannot be applied to all levels of integrated design along the spectrum. Fee structures need to be modified heavily as a design is delivered through successively higher levels of integration.

Figure 3 shows the relative cost and energy performance impacts for the spectrum of integration. Implementation cost here refers to the hard costs of incorporating technologies into a building. The two highest levels of integration for *Reduce Building Size* and *Eliminate Building* are obviously higher in terms of energy performance, with relatively low implementation costs. Both of these require some design effort to be able to share building use or design an alternative use strategy that allows building elimination. While this may not be traditional building design, it is still an operational design effort. For these integration levels, implementation costs will often be negative since building areas may be completely eliminated. The scaling also shows that if energy performance were to be held roughly constant between *Simple Bundling* to *System Elimination* across the spectrum, implementation costs reduce and design costs increase while moving up the integration spectrum. It is possible that, in many cases, the increased design costs will only be fraction of the implementation costs reduced, thus resulting in a net cost savings to the project. ***Figure 3*** can provide certain insights on the relationships between the three dimensions considered. For example it is possible to conclude that buildings owners can demand a high energy performance at a low incremental first cost if they are willing to provide additional design fees. Designers can recognize that such a scenario will require design and cost integration possibly to the extent of doing single or multi-interaction bundling. These levels of integration require parametric energy analysis, detailed cost interaction accounting, and multiple load calculation for HVAC systems; *Figure 2* can provide insights that will allow them to negotiate a fee distribution that is heavy on early design, while *Figure 3* allows them to negotiate extra design fees in lieu of lower implementation (capital) costs. These two figures thus provide a framework for communication of the performance and cost parameters as the first step towards successful contract negotiation to reduce the owner or designer's perception of risk.

COST INTERACTIONS

To understand how the various design parameters relate to one another in terms of possible cost interactions, a matrix of typical architectural and engineering design decisions was analyzed, as shown in *Figure 4*. While not exhaustive, the list of decisions includes:

Architectural: Glazing U-factor, glazing solar heat gain coefficient (SHGC), glazing visible transmittance (vt), window size, window shades, wall insulation/ thermal mass, roof insulation, interior reflectances, ceiling height, floor to floor height, and structural design

Lighting systems: Lighting power density, occupancy sensor control lighting, and daylighting control

Mechanical systems: Heating plant size, cooling plant size, supply air flow rate, ventilation air quantity, CO_2 control of outdoor air, occupancy sensor control of outdoor air, and heat recovery

Each element of the first column was assessed for its effect on the elements listed across the matrix. The effects were rated as *direct impact, indirect impact,* or *no impact* on the other parameters. An example of a direct impact is that lighting power density directly affects the cooling load and thus the cooling plant size. An example of an indirect impact is that the interior paint reflectance affects the cooling system size by first affecting the lighting power density (lumens required), which then contributes to the cooling load.

Causes \ Effects	Lighting Power Density	Heating plant size	Cooling plant size	Supply air/duct/fan size	Glazing U-factor	Glazing SHGC	Glazing VT	Window Size	Window overhangs	Wall Insulation/ mass	Roof Insulation	Interior reflectances	Ceiling Height	Floor to floor height	Structural design	OS Control Lighting	Daylighting Control	Ventilation air quantity	CO2 control of OA	OS control of air	Heat Recovery	Building orientation
Lighting Power Density		2	2	2													2					
Heating plant size															1							
Cooling plant size															1							
Supply air/duct/fan size		2	2										2	2	1							
Glazing U-factor		2	2					2									2					
Glazing SHGC	2	1	1														2					
Glazing VT	2	1	1	2										2	1		2					
Window Size																						
Window overhangs																						
Wall Insulation/mass		2																				
Roof Insulation		2	2	2			2															
Interior reflectances						2											2					
Ceiling Height		2	2	2	2	2											2					
Floor to floor height		2	2	2				2														
Structural design		2	2	2																		
OS Control Lighting		2	2	2																		
Daylighting Control		2	2														2			2		
Ventilation air quantity		2	2													2						
CO2 control of OA		2	2	2																		
OS control of air		2	2																	2		
Heat Recovery		2	2													2			2			
Building orientation		2	2																			

1 = Indirect Impact, 2 = Direct Impact

Parameters that are directly affected by others

Parameters that directly affect others

Figure 4. Matrix of cost interactions amongst design parameters identifying direct and indirect impacts

Cause \ Effects	Lighting Power Density	Heating plant size	Cooling plant size	Supply air/duct/fan size	Glazing U-factor	Glazing SHGC	Glazing VT	Window Size	Window overhangs	Wall Insulation/ mass	Roof Insulation	Interior reflectances	Ceiling Height	Floor to floor height	Structural design	OS Control Lighting	Daylighting Control	Ventilation air quantity	CO2 control of OA	OS control of air	Heat Recovery	Building orientation
Lighting Power Density		2	3	2													3					
Heating plant size															I							
Cooling plant size															I							
Supply air/duct/fan size		3	3										2	2	I		2					
Glazing U-factor		3																				
Glazing SHGC		1	3	3			1															
Glazing VT						1											3					
Window Size		3	3	3	3	3											3					
Window overhangs		1	2	2				1														
Wall Insulation/mass		3	2	1																		
Roof Insulation		3	1	1																		
Interior reflectances	3	I	I														3					
Ceiling Height	3	I	I	2										2	I		3					
Floor to floor height																						
Structural design																						
OS Control Lighting		1	1														2			3		
Daylighting Control		1	1													2						
Ventilation air quantity		3	3	1																		
CO2 control of OA		2	2																	3		
OS control of air		2	2													3			3			
Heat Recovery		3	3																			
Building orientation		3	3					2									3					

simple

simple

Direct Impact Potential of Causes on effects: 3= High, 2=Medium, 1=Low

Complex interactors that have medium or high impact on others and others have medium or high impact on them

Figure 5. Matrix of direct impact potential for cost interactions amongst design parameters

As depicted in *Figure 4*, the results of this relational analysis show that heating plant size, cooling plant size, and daylighting control are affected more often than any other parameter; the impacts on the plant size are also most often direct as opposed to indirect. However, design teams generally place a lower priority on the effect on plant size when assessing design parameters. For example, window size is more often rated on criteria such as aesthetics and cost of window construction.

The next step was to better understand the magnitude of impacts of the design parameters. The direct impacts were rated as *high, medium,* or *low* based on whether the effect on the parameters would result in a significant change or only a small change. See *Figure 5*. The design parameters with high impact on cooling plant size are lighting power density, supply air quantity, duct size, glazing characteristics, window size, ventilation air quantity, and heat recovery. For heating plant size, insulation is added to the previous list, and lighting power density is omitted. Daylighting controls are highly affected by multiple factors, which is why they are more complex to successfully implement (Vaidya, 2005 and Greden, 2006).

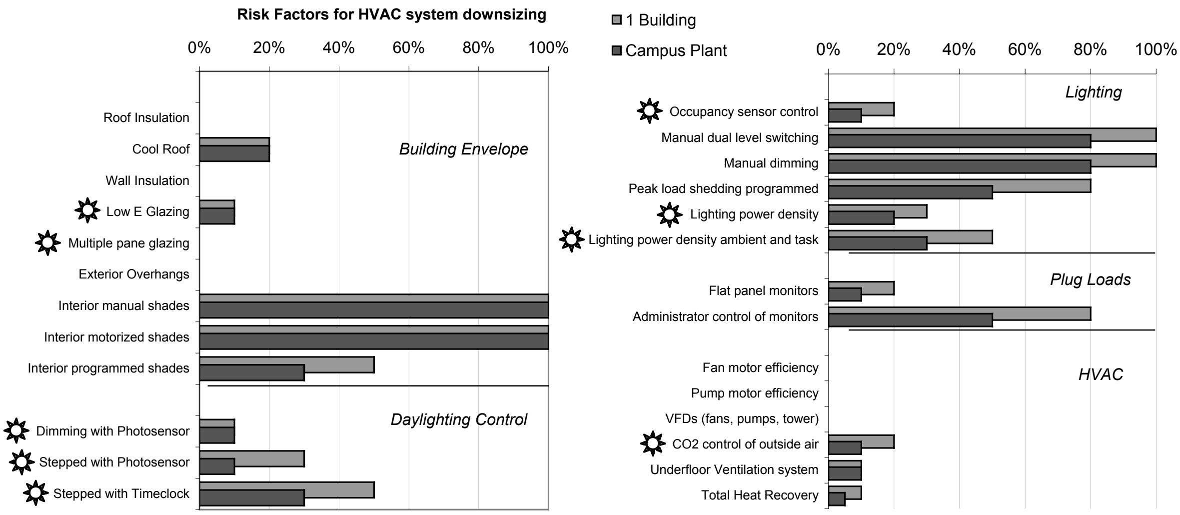


Figure 6. Level of certainty (risk) for design parameters in their impact on downsizing cooling and heating plants

Several parameters have multiple impacts. Supply air quantity and duct size have high impacts on plant sizes, including fan and pump sizes, and medium impacts on ceiling and floor-to-floor heights. Window sizes and building orientation also have multiple high impacts, including plant size, fan/pump size, glazing characteristics, and daylighting controls. Interior reflectance and ceiling heights have high impacts on lighting power density and daylighting control potential. Other parameters have low impacts. Lighting controls such as occupancy sensors have low impacts because they do not reduce loads significantly at peak times means; CO_2 control of outside air has low impacts on plant sizes for the same reason.

The next step was to look at interactions amongst the design parameters. Items are not exclusive to only the cause or just the effect list because design is systemic. Those items with scores greater than 2 as both a cause and effect are deemed "complex interactors." There are nine complex interactors: lighting power density, supply air/ duct size, glazing U-factor, glazing SHGC, ceiling height, occupancy sensor control of lighting, daylighting control, CO_2 control and occupancy sensor control of VAV boxes/outdoor air. The implication for integrated costing is that whenever the costs of complex interactors are estimated, an additional costing exercise should be done to account for their domino effect. For example, for various lighting power density alternatives, the effects on heating and cooling plant sizes, supply air/duct sizes, and daylighting system components (e.g., number of ballasts), needs to be considered. Likewise, for various window size alternatives, the design and cost impact on plant size, glazing characteristics, and daylighting control capability (more or less zone depth) needs to be considered. When considering occupancy sensor control of lighting, the possibility of sharing the occupancy sensors for control of VAV boxes will affect the costs of outdoor air control methods (CO_2 control of outdoor air or using the already existing occupancy sensors to control VAV boxes/outdoor air). These implications will be explored in the design tool and case study presented in the next section.

RISKS FOR PLANT DOWNSIZING

Next, this methodology addresses the uncertainty of impact of design parameters on plant sizes. Engineers are likely to take an "all or nothing" approach where the small amounts of uncertainty will result in the effect of a design parameters not being taken in to account. Since a high-performance building is likely to have a number of energy conservation strategies, the uncertainty of these impacts can be seen in the form of risk that can be diversified amongst the various strategies considered. This risk can be further diversified where a central cooling or heating plant serves multiple buildings, as on a campus.

Figure 6 [4] shows the rating of a variety of design parameters for their level of certainty (or risk) in being able to downsize plants. A zero means "no risk", or the load reduction associated with the savings are certain, while a one means "high risk," or that the design strategy cannot be relied upon to provide load reductions that would allow for reduced plant size. The complex interactors listed above are marked with a star. Their ratings are no more than 0.5, meaning they are on the low-risk half of the scale for being able to downsize HVAC systems. Glazing characteristics are relatively certain, with risk scores of 0.1 or less. Daylighting control strategies, assuming they are implemented properly, are also relatively low-risk with their best performance coinciding with cooling peak loads. They are rated at 0.3 or less for stepped or dimming controls and 0.5 or less for time-clock control. Occupancy sensor control of lighting also has a relatively low-risk impact on being able to reduce plant sizes. This assumes a building with a fair amount of diversity in space use. Conversely, a building that has most of its spaces occupied for most of the day would have a score near 1.0. Lighting design is lower risk for ambient lighting as compared to a combined ambient-task lighting strategy. CO_2 control of outside air, as it is usually applied to high volume, high-occupancy spaces, also has a relatively low risk factor for plant size reduction.

Another approach to address the uncertainty in impact on heating and cooling plant size is to design a staged capacity sys-

4. The level of uncertainty shown here is the authors' assessment based on their professional experience.

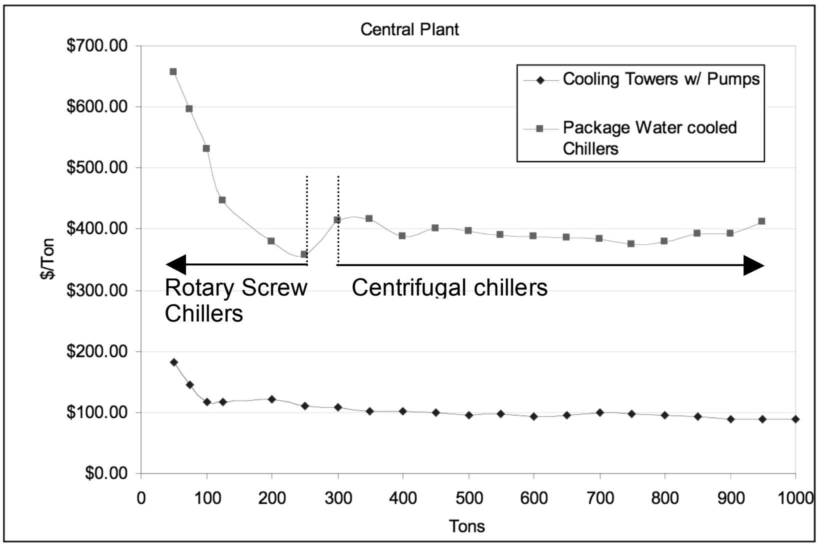


Figure 7. System cost for Central Plant equipment expressed as a function of capacity in cooling tons. Based on data from RS Means (2006).

tem where plant equipment is deployed in series, and operation is scheduled for varied use to keep it operating at best efficiency. This approach can also be used to avoid purchasing the peak-load equipment until its need has been proved through actual building use.

SYSTEM SIZE REDUCTION COST ESTIMATES

Cullen (2005) lists the four primary methods used for estimating construction costs as Parametric or Project Comparison Estimating, Area and Volume Estimating, Assembly and System Estimating and Unit Price and Schedule Estimating. Each method requires a level of information and offers a level of confidence that is directly related to the amount of time required to prepare the estimate. Of these four methods, the Parametric Estimating and the Assembly and Systems Estimating methods are suited for comparing alternatives (Cullen, 2005). The Parametric method is used early in the process when adequate design information is not available, and this method can have up to a 25 % margin of error; this method can be used effectively for the two highest levels of integration that require pre-design cost estimation (Cullen, 2005). The Assembly and Systems Method requires design information to be developed and the resulting margin of error can be less than 10 % (Cullen, 2005). This method combines components into an overall system or assembly where the size of the system in conjunction with values from assembly cost data guides yields the system cost estimate. Integrated cost estimation is an exercise in evaluating system interactions for impacts on size metrics. Thus the Assembly and Systems Method is ideally suited for integrated costing.

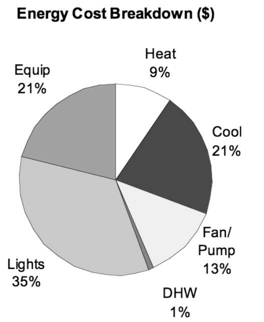
Using size metrics and assembly cost data has some issues for accurate estimates of HVAC systems. For example, the cost of a well-field for a ground source heat pump system is closely proportional to the cooling capacity required, since it is possible to eliminate each well from the field as the system load is reduced. However, the cost of the distributed heat pump units does not scale that closely with size. ***Figure 7*** is based on cost data developed from RS Means (2006) and shows that the cost of chillers and cooling towers, expressed as a function of cooling capacity, also rises as the capacity reduces. The relationship between cost and sizes is not linear. The functions for these variables for various systems and their components will need to be studied further to find similarities and unique cases. Size-cost functions for various components will need to be developed to assist in cost estimation.

Cost data guides such as RS Means (2006) have cost data where resultant functions express themselves as relatively smooth curves. *Figure 7* shows that since centrifugal chillers are typically available above 300 tons and screw chillers are typically available below that threshold, the cost-size relationship follows a step functions. Besides this, step functions can also be caused by the availability of sizes from specific manufacturers. Further research will be needed to test the sensitivity of these steps as it relates to the process of integrated cost estimating. If the impact of is significant, sophisticated functions will need to be developed for use in estimation tools.

Case Study[5]

The case study uses a 3-story, 6,000 m^2 office building proposed in Las Vegas, Nevada (U.S.A.). The building is oriented with its largest facades facing north and south, with open office spaces on the perimeter. The office spaces are daylit with window head heights and ceilings at 3.5 m, a window to floor area ratio of 16 % and a window to wall area ratio of 31 %. The mechanical system includes six variable air volume, evaporatively-cooled direct expansion units, and a central gas boiler. All spaces in the building are heated and cooled. The energy code baseline was ASHRAE 90.1-1999, and energy savings for all ECMs are compared to this baseline. The baseline simulation shows a cooling capacity requirement of 149 tons. Parametric energy modelling was done with DOE-2.1E using the local weather file, and utility rates and energy savings for each parametric run or strategy

5. The energy analysis, simulation and calculations for this case study were done by the authors at The Weidt Group based on an actual building project. The incremental costs for the strategies were assessed by the designers on the project, and the mechanical system costs and potential for downsizing were estimated by Axiom Engineers.



Energy Cost By End Use	
Heating	$7,875
Cooling	$17,754
Fans / Pumps	$10,794
DHW	$685
Refrigeration	$0
Lighting	$28,563
Equipment	$17,612

Figure 8. Annual energy simulation results for the baseline building ASHRAE 90.1-1999

were calculated by comparing with the baseline. Incremental costs for the strategies were developed by a cost estimator on the design team.

Figure 8 shows energy simulation results for the baseline building, and detailed results for energy cost, cooling capacity, heating capacity and incremental costs and simple payback for various ECMs are shown in the Appendix. The design base included ECMs that were already included in the design team's standards of practice. To demonstrate the difference in perceived incremental costs at varying levels of cost estimation integration, four alternatives are compared herein.

Alternative 1 is at the lowest end of the integration spectrum, where there is no thought to integration. Individual ECMs that had a payback of less than five years are included and other ECMs are excluded. This alternative includes improved roof insulation and glazing, dimming daylighting controls, occupancy sensor control and dual level switching of lighting, a direct lighting system with Super T8 lamps, efficient pump motors, variable frequency drives (VFDs), and demand control ventilation.

Alternative 2 uses the Simple Bundling approach described above to include ECMs such that the overall bundled payback stays below five years. This alternative adds wall insulation, other daylighting controls, more lighting controls, efficient fan motors, more VFDs, and total heat recovery.

Alternatives 3 and 4 go further up on the interaction spectrum and uses the single (cost) interaction approach. Here the impact of all ECMs on the cooling and heating system capacity is taken into account. The ECMs in these two alternatives are the same. Alternative 3 treats all ECMs as risk-free and uses the entire extent of equipment downsizing as predicted by the simulation models. Alternative 4 applies the risk factors noted in ***Figure 6*** to discount the extent of downsizing predicted by the simulation models. Cooling capacity is simplistically valued at $ 3,000 per ton and heating capacity is valued at $ 5 per kBtu/hour; a more sophisticated estimation methodology will eventually use different metrics and related values for components of the system, such as cost/cfm (cubic feet per minute) of supply air, cost/ton for cooling units, etc. For most commercial buildings, airflow and duct sizes are determined by the cooling needs and the heating capacity cost here reflects only the cost of the boiler. Alternatives 3 and 4 add more ECMs to Alternative 2: direct lighting is replaced with a direct-indirect lighting system, and computer monitors are flat panel LCDs. Note that these ECMs enhance the quality of the workspace and experience in addition to being energy efficient.

Energy savings calculated through the simulation process described above and the reported incremental costs are shown in the Appendix for each individual strategy. Cumulative results for the above alternatives are shown in Table 1. Figure 9 summarizes the percent of energy savings compared to the baseline and net incremental costs.

As shown in *Table 1* and *Figure 9*, the Design Base is better than the baseline with a 9 % energy savings due to the ECMs implicit in the design. Alternative 1 achieves a 34 % energy savings with a $ 68,000 first cost resulting in a 3.3 year payback. Alternative 2, with a focus on the bundled payback of less than five years, achieves 37 % energy savings with a $ 112,000 incremental first cost. Alternatives 3 and 4 both achieve 42 % energy savings with $ 12,000 and $ 39,000 incremental costs and 0.5 and 1.4 year payback respectively. Alternatives 3 and 4 are able to count a 56 and 47 ton cooling capacity reduction, about a one-third cooling capacity reduction compared to the baseline scenario. While Alternative 3 may be an unrealistic scenario with no risks assigned to any ECM, Alternative 4 provides a more feasible downsized alternative; the perceived incremental cost for Alternative 4 is lower than that of Alternatives 1 and 2 and with a higher energy savings, the payback is also more attractive to a decision maker. Within the spectrum of integration methods studied here, the higher level of integration demonstrates an effective reduction of the first cost barrier.

Conclusion

Integrated design necessitates an associated integrated costing methodology to overcome the perceived first-cost barriers of high-performance building design. Integrated design and costing shifts the levels of effort to earlier design phases and increases effort by, and cooperation amongst, design team members. It is a methodology that can succeed over repeated collaborations as design teams build trust and familiarity with such a systemic approach of design and costing. The spectrum of possible integration presented, from simple bundling to elimination of systems, provides a roadmap to guide pursuits of integrated design and a framework for communication of the performance and cost parameters as the first step towards successful contract negotiation to reduce the owner or designer's perception of risk. The design elements that have iterative interactions with others as a systemic design is modified are identified as lighting power density, supply air and duct size, glazing U-factor, glazing SHGC, ceiling height, occupancy sensor control of lighting, daylighting control, CO_2 control and occupancy sensor control of air flow; heating and cooling plant capacity and supply air and duct size are most often affected by other parameters. Overall, these parameters can be considered as the focus of the integrated cost estimation exercise for typical medium sized commercial buildings.

The Assembly and Systems Method is identified as the cost estimation method ideally suited for integrated costing. Example cost-size functions for HVAC systems based on data from assembly cost guides are presented. These functions need further study towards developing a robust methodology for integrated cost estimating tools.

Table 1. Percent Energy Savings and Perceived Incremental First Costs for the Alternatives

Case	Design Base	Alt 1	Alt 2	Alt 3	Alt 4
Integration Level	Design Base	No Integration	Simple Bundling	Single Interaction	Single Interaction
Criteria	ECMs implicit in Design	Individual ECM Payback < 5yr	Bundled Payback < 5yr	HVAC capacity reduction no risk factors	HVAC capacity reduction with risk factors
Energy Savings	$7,152	$28,069	$30,667	$34,798	$34,798
% Energy Savings	9%	34%	37%	42%	42%
Cooling Ton Savings	na	na	na	56	47
Heating KBtuH Savings	na	na	na	77	98
Cooling Capacity $ Savings	na	na	na	$168,188	$141,067
Heating Capacity $ Savings	na	na	na	$386	$491
Incremental First Cost	$0	$68,649	$112,476	$12,513	$39,529
Simple Payback	n/a	3.3	4.8	0.5	1.4

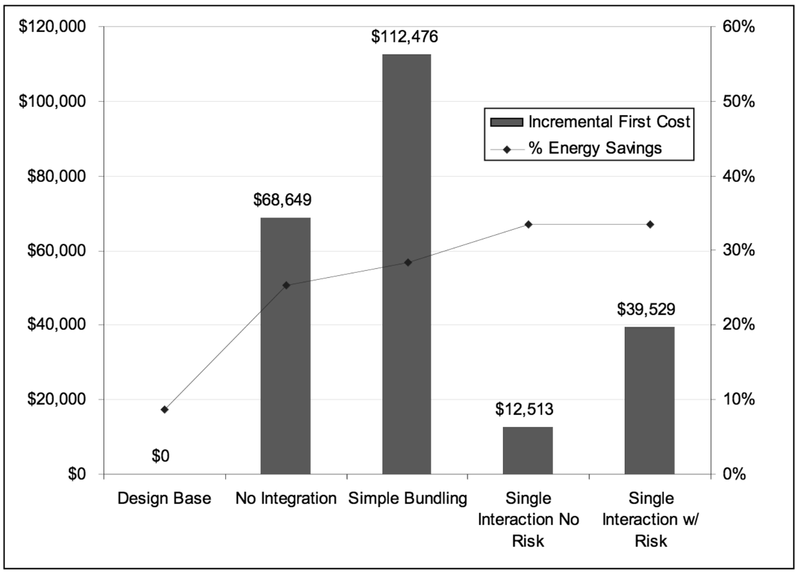


Figure 9. Percent Energy Savings and Perceived Incremental First Costs for the Alternatives

HVAC system sizing can be greatly improved through an integrated design and costing methodology. As demonstrated in the office building case study, greater energy conservation can be achieved with lower first costs when reductions in HVAC system sizing are considered. Risk factors for sizing consideration can be analyzed such that the system sizing is based on a rational framework. As integrated design and costing is adopted in practice, further study is needed to understand the level to which first cost barriers are reduced. This will provide information to policy-makers to further encourage adoption of the practice and thus greater energy savings.

Several policies can encourage the practice of integrated design and cost estimation to reduce the perceived first cost barrier: 1) similar to the requirements for lifecycle costing by some government organizations and public agencies, integrated costing could also be required to assure that capital cost savings are accounted for in integrated design; 2) public agencies can lead the market by changing the design fee structures to recognize greater importance of early design consideration of cost integration. Design fees should be decoupled from capital cost expenditure for equipment; 3) utility rebates and tax deduction programs can also encourage integrated design of building systems by providing high incentives to the designers for overall building energy performance. These design incentives should be decoupled from reported incremental costs; 4) provide funding support to develop publicly available cost databases and costing functions for system or assembly cost estimation; and 5) develop best practice case studies that show how design teams save owners' money through integrated designs.

References

Davis, D. 2007. *BIM (Building Information Modeling) Update*. The American Institute of Architects. http://www.aia.org/tap_a_0903bim

Deru, M., Torcellini, P., Sheffer, M., and Lau, A. 2005. *Analysis of the Design and Energy Performance of the Pennsylvania Department of Environmental Protection Cambria Office Building.* Colorado. National Renewable Energy Laboratory.

Cullen, S. 2005. *Estimating*. http://www.wbdg.org/design/estimating.php

Eto, J., Prahl, R., and Schlegel, Jeff. 1996. *A Scoping Study on Energy-Efficiency Market Transformation by California Utility DSM Programs.* California. Earnest Orlando Lawrence Berkeley National Laboratory.

Flynn, K. 2006. Architect. Personal communication. December 26.

Gouveia, K. 2006. Architect. Personal communication. December 20.

Greden, L., Vaidya, P., Eijadi D. 2006. *Flexibility and Advanced Energy Design with Convia*. http://www.twgenergy.com/Research/Convia.htm

Kats, G., Alevantis, L., Berman, A., Mills, E., and Perlman, J. 2003. *The Costs and Financial Benefits of Green Buildings: A Report to California's Sustainable Building Task Force*. October 2003. http://www.usgbc.org/Docs/News/News477.pdf. Cited 21 January 2005.

Kutilek, F. 2005. *Identifying the real cost of seeking LEED certification.* Estimating Today, March 2005 pp 11-15.

Lowe, C. 2007. Marketing and public relations coordinator at the Rocky Mountain Institute. Personal Communication. March 26.

Market Transformation to Sustainability. 2006. Whole System Integration Process (WSIP) Guideline Standard. Draft for Comment. September.

Mathiessen L., Morris, P. 2004. Costing Green: *A Comprehensive Cost Database and Budgeting Methodology.* September.

NIBS National Institute of Building Sciences. 2007. *Whole Building Design Guide.* http://www.wbdg.org

Office of Financial Management State of WA (OFM-WA). 2006. *Guidelines for Determining Architect/Engineer Fees for Public Works Building Projects*. http://www.ofm.wa.gov/budget/instructions/capinst/appendixb.pdf

Reed, W. 2007. Architect. Personal communication. January 3.

Rocky Mountain Institute, 2006. http://www.rmi.org/sitepages/pid379.php

RS Means, 2006. *2006 RS Means Mechanical Cost Data.* 29th ed. Kingston: RS Means CMD, 2006.

Seely, R. 2006. Architect. Personal communication. December 20.

Schaffner, C. 2006. Energy Consultant. Personal communication. December 20.

Sheffer, M. 2006. Energy Consultant. Personal communication. December 20.

Steven Winter Associates, Inc. 2004. *LEED® Cost Study.* October.

Torcellini, P., Pless, S., Deru, M., Griffith, B., Long, N., and Judkoff, R. 2006. *Lessons Learned from Case Studies of Six High-Performance Buildings*. Colorado. National Renewable Energy Laboratory.

Vaidya, P, McDougall, T, Steinbock, T, Douglas J, Eijadi, D. 2004. *Where It Goes Wrong and How Users Respond to Failure*. In Proceedings of ACEEE 2004 Summer Study.

Vaidya, P, McDougall, T, Steinbock, T, Douglas J, Eijadi, D. 2005. *Making Daylighting Work Learning from failures to improve the design and implementation process.* In Proceedings of ECEEE 2005 Summer Study.

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Appendix

Energy Conservation Measure	Savings vs. 90.1-1999 Cooling Tons	Savings vs. 90.1-1999 Heating KBtuH	Savings vs. 90.1-1999 annual energy	Compared to Design Base first cost	Compared to Design Base pay back	Design Base	No Integration Alt 1	Simple Bundling Alt 2	Single Interaction Bundling Alt 3	Single Interaction Bundling Alt 4
Envelope Insulation Strategies										
R-30 roof; 90.1-99	0.0	0	0	$0	n/a	X	X	X	X	X
R-40 roof insulation	1.2	19	124	$32,524	262.3					
White roof	1.7	-6	118	$0	n/a	X	X	X	X	X
R-13 wall; 90.1-99	0.0	0	0	$0	n/a	X	X			
R-16 wall insulation	0.5	27	290	$11,347	39.1			X	X	X
R-20 wall insulation	1.0	36	457	$56,734	124.1					
Window Glazing Strategies										
Lo E clear 2/alum frame	-2.4	124	174	($25,423)	n/a					
Lo E tint 2/alum frame	3.8	96	1,234	($20,338)	imm					
Lo E clear, high VT	2.9	114	1,004	$0	n/a	X	X	X	X	X
Lo E tint, high VT	4.5	103	1,294	$5,085	17.5					
Overhangs on South face	1.5	1	205	$0	n/a	X	X	X	X	X
Daylighting Control Strategies										
Open office stepped daylighting	3.6	-8	3,528	$5,490	1.6					
Open office dimming daylighting	10.5	-29	10,210	$24,080	2.4		X	X	X	X
Lobby stepped daylighting	0.1	-1	74	$620	8.4			X	X	X
Dining stepped daylighting	0.0	0	5	$335	67.0					
Dining dimming daylighting	0.0	0	17	$950	55.9			X	X	X
Conference stepped daylighting	0.3	-1	188	$2,330	12.4					
Conference diimming daylighting	0.6	-6	420	$5,250	12.5					
Lighting Control Strategies										
Corridor occupancy sensor control	0.1	-4	132	$1,128	8.5					
Storage occupancy sensor control	0.3	-8	315	$2,400	7.6			X	X	X
Restroom occupancy sensor control	0.3	-5	271	$1,128	4.2		X	X	X	X
Dining occupancy sensor control	0.0	-1	5	$243	48.5			X	X	X
Dining dual level switching	0.0	0	5	$31	6.1			X	X	X
Dining manual dimming	0.0	0	6	$90	15.0					
Open office occupancy sensor control	1.5	-103	4,792	$20,000	4.2		X	X	X	X
Open office dual level switching	1.6	-19	1,998	$803	0.4					
Private office occupancy sensor control	0.6	-19	1,851	$1,800	1.0		X	X	X	X
Private office dual level switching	0.4	-2	716	$1,787	2.5		X	X	X	X
Conference occupancy sensor control	0.4	-13	383	$2,820	7.4			X	X	X
Conference dual level switching	0.2	-3	178	$828	4.7		X			
Conference manual dimming	0.3	-4	294	$2,420	8.2			X	X	X
Lighting Design Strategies										
Open office direct system at 50 fc	6.3	-64	7,416	$0	n/a	X	X	X		
Open office indirect system at 50 fc	4.9	-47	5,408	$52,147	n/a					
Open office task (0.3 W/sf) ambient at 30 fc	6.3	-64	7,416	$4,346	n/a					
Open office direct/indirect system at 40 fc	6.8	-68	7,955	$28,247	52.4				X	X
Private office direct system at 50 fc	0.3	0	515	$0	n/a	X	X	X		
Private office indirect system at 50 fc	-0.3	3	-718	$11,725	n/a					
Private office task (0.3 W/sf) ambient at 30 fc	0.6	-8	1,283	$0	0.0					
Private office direct/indirect system at 40 fc	0.5	-5	1,007	$4,467	9.1				X	X
Conference direct system at 50 fc	0.3	-4	278	$0	n/a	X	X	X		
Conference indirect system at 50 fc	0.1	-2	116	$8,223	n/a					
Conference direct/indirect system at 40 fc	0.3	-8	313	$4,898	139.9				X	X
Grouped Super T-8	3.4	-39	4,098	$8,488	2.1		X	X	X	X
Fan and Pump Strategies										
Code motor efficiencies	0.0	0	0	n/a	n/a					
Premium efficiency supply/return fan motors	0.1	-1	104	$1,125	10.8			X	X	X
Premium efficiency pump motors	0.0	0	92	$188	2.0		X	X	X	X
VFDs on supply/return air fans	0.0	0	0	$0	n/a	X	X	X	X	X
VFD on heating pump	0.0	0	639	$2,700	4.2		X	X	X	X
VFD on cooling pump	0.0	0	485	$2,700	5.6			X	X	X
VFD on cooling twr fan	0.0	0	1,242	$2,700	2.2		X	X	X	X
Conditioning of Outside Air Strategies										
CO2 control of outside air	16.5	191	1,096	$3,450	3.1		X	X	X	X
Underfloor Ventilation system	22.7	-49	4,524	$678,343	149.9					
Total Heat Recovery	34.4	186	1,671	$20,000	12.0			X	X	X
Domestic Hot Water Strategies										
Code DHW system	0.0	0	0	$0	n/a	X				
85% DHW Efficiency	0.0	0	171	$750	4.4					
95% DHW Efficiency	0.0	0	243	$1,000	4.1		X	X	X	X
Plug Load Strategies										
Flat panel monitors	3.3	-36	4,441	$31,000	7.0				X	X
Administrator control of monitors	1.3	-29	2,461	$500	0.2		X	X	X	X