

Linking Energy to Health and Productivity in the Built Environment

Evaluating the Cost-Benefits of High Performance Building and Community Design for
Sustainability, Health and Productivity

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ABSTRACT

While an ever increasing number of clients and professionals are committed to achieving high levels of energy and environmental standards in new and retrofit projects, the investment community still has not moved beyond first cost decisionmaking. The need for life cycle decisionmaking will depend on multiple national and international efforts to develop the financial algorithms and collect the databases demonstrating the link between high performance buildings and energy, environmental, health and productivity benefits. This paper introduces *e-BIDS*[™], a web-based life cycle decision support tool under development for the cost-benefit analysis of the DOE data base of high performance building components, systems and whole building projects. This DOE interactive tool is linked to *BIDS*[™] - the building investment decision support tool that has been developed by the NSF/IUCRC Center for Building Performance at Carnegie Mellon University, with the support of the Advanced Building Systems Integration Consortium (ABSIC). The cost-benefit decision support tool presents the results of field case studies, laboratory studies, simulation, and other research, clearly demonstrating the relationship of quality building investments for workstation, central system and whole building/LEED design approaches to multiple cost benefit factors. The *BIDS*[™] tool is more fully described in "Building Investment Decision Support (BIDS)" published in the Austin Papers – the Best of the 2002 International Green Building Conference (Loftness and Hartkopf 2002).

1. CONFLICTS BETWEEN COST, ENERGY AND ENVIRONMENTAL QUALITY?

There are two debates that consistently hamper the drive to improve indoor environmental quality in U.S. buildings. First, many environmentalists argue that improving indoor environmental quality does not cost more (Figure 1a), while many building owners argue that the increased first costs for high performance buildings cannot be considered in today's market.

While the first critical moves in environmental design and engineering, including orientation, layout, and the use of passive conditioning systems, may not have to increase first cost, the selection of high performance materials, components and systems will have to increase first cost (Figure 1b). We must be clear: a high performance light fixture, lamp and dimmable ballast will cost more than “the contractors special”- yet will always demonstrate a measurable life cycle value benefit. As a result, it is critical for the environmental design community – architects and engineers alike – to build the proof sets demonstrating the life cycle value of high performance materials, components and assemblies. Both the computer and the car industry sells quality differences component by component with a ten to one price differential. The building industry sells cost/sq.ft. – with the continued measure of success being the lowest price for the package with no record of the quality of the parts.

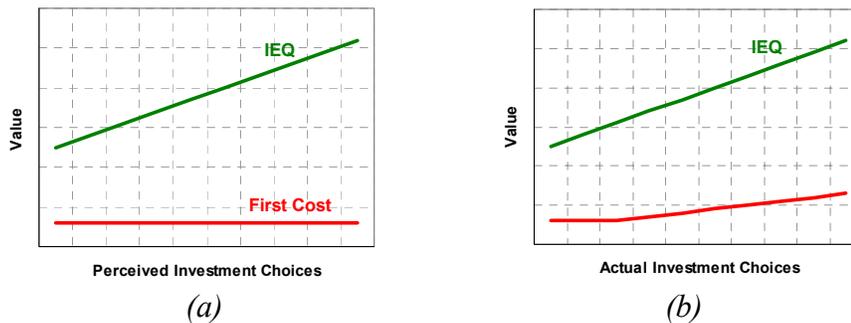


Figure 1 First Cost and quality of indoor environments

The second debate that consistently hampers the drive to improve indoor environmental quality in U.S. buildings is the belief that improving the quality of indoor environments must perforce cost more energy (Figure 2a). While there may be a few challenging conflicts for architects and engineers, the goal of improving indoor environmental quality is actually proving to measurably reduce energy and other environmental costs, and to dramatically improve business performance (Figure 2b). Indeed, the synergies are significant – improved temperature control, air quality, lighting control, and access to the natural environment will result in measurable productivity, health, environment, facility management, churn, waste, emissions, attraction/retention, and energy savings. Nonetheless, the proofs must be collected and documented by the owner/occupant/design or federal and industrial community if consistent first-cost investment in quality buildings are to reap these near and long term cost-benefits.

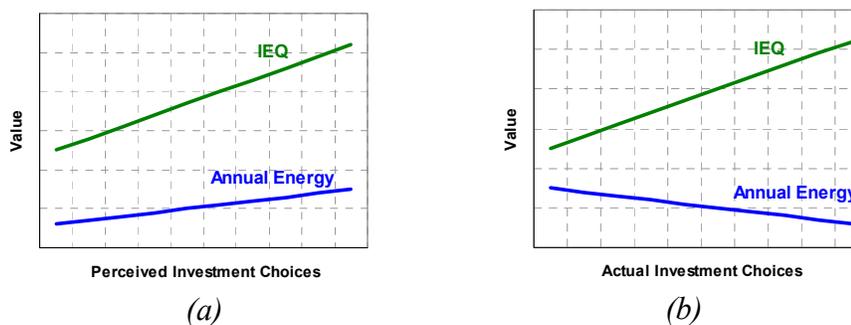


Figure 2 Annual Energy and quality of indoor environments

2. PROOF SETS IN HAND

The Center for Building Performance & Diagnostics (CBPD) in collaboration with the Advanced Building Systems Integration Consortium (ABSIC), has been avidly pursuing proof sets from around the world that link improved building environmental quality to life cycle cost-benefits. For each 1000 abstracts reviewed and 100 promising papers read, one case study with statistically significant data can be identified. With over four years of graduate attention, the BIDS™ tool now has 140 case studies, with approximately 50 linking high performance components and systems to energy as well as other life cycle benefits. The initiation of the *e*-BIDS effort with the Department of Energy and LBNL is driven to capture additional energy related case studies system by system as well as to enhance the life cycle analysis to more deliberately address the broader array of energy cost-benefits to include peak power, power reliability, pollution and waste (Figure 3).

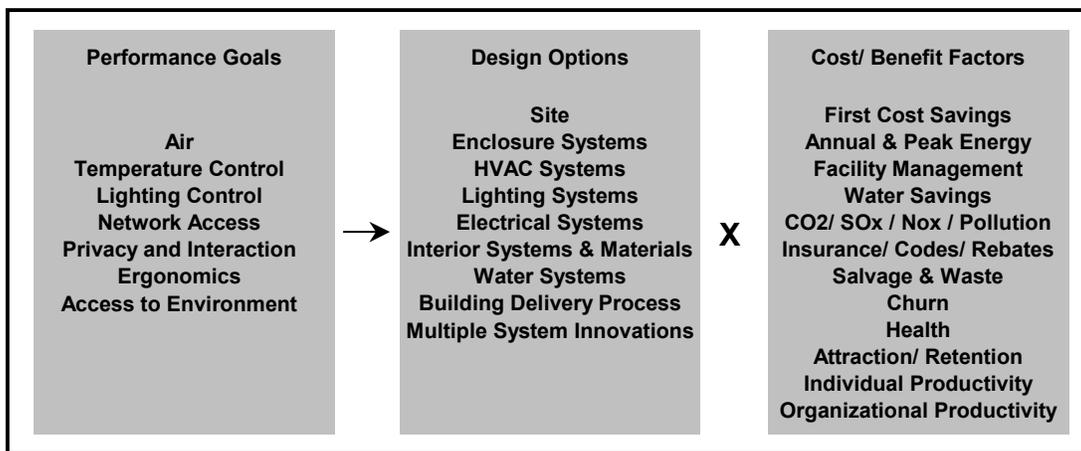


Figure 3 *e*-BIDS matrix

2.1 Temperature Control for Thermal Comfort and Environmental Quality

The CBPD/ ABSIC guidelines for high performance buildings argue for at least eight guidelines for improving thermal comfort in buildings:

- Decouple ventilation and thermal conditioning
- Engineer mixed-mode conditioning with natural ventilation
- Engineer for dynamic thermal zone sizing
- Engineer for individual control of thermal conditions
- Minimize enclosure heat loss and heat gain
- Design for thermal load balancing
- Specify high performance, plug and play HVAC assemblies
- Innovate with user-responsive automation

While all of these guidelines may increase first cost, none of these guidelines should create any additional energy costs, and indeed should reduce thermal energy loads by 20-60%. Proof sets for minimizing enclosure heat loss and heat gain are easily developed by simulation and

accounting. However, the importance of mixed mode conditioning and individual control of thermal conditions – which require engineering innovation and first cost investment critically needs the following proofs:

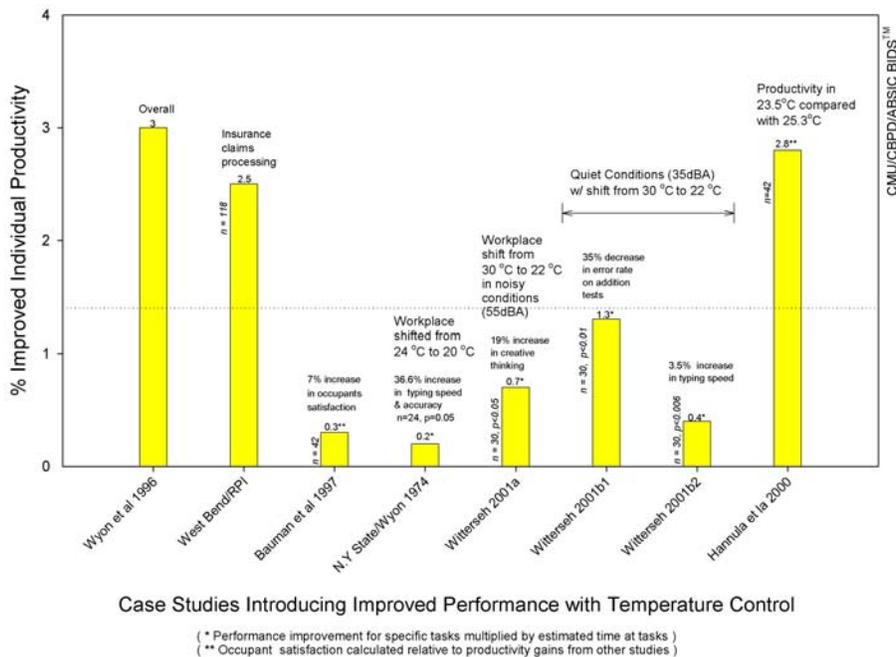


Figure 4 Temperature Control Increases Productivity and Reduces Energy Use.

The ability for individual workers to control the temperature at their workstation has been shown to improve individual productivity at a range of tasks from typing and addition to creative thinking by 3.5-36.6% (Figure 4). The provision of thermal control for individuals can be achieved through task conditioning, or individual unit controls for temperature, air speed and air direction – most achievable in HVAC systems that have decoupled ventilation from thermal conditioning.

To date, the CBPD team has identified eight case studies linking the benefits of providing individual temperature control for each worker to measured productivity gains. Given assumptions about the percent of time spent at various tasks, these eight studies demonstrate from 0.2 to 3% increases in overall productivity. One study demonstrates that individual temperature control combined with responsive central systems can also yield energy savings of 43%, a gain that can only grow with flex-work schedules. One simulation study identified a 14% reduction in HVAC energy use with smaller HVAC zone sizes, occupancy sensors and broadband set points.

While a first cost penalty is assumed for the provision of individual control for most of these studies, the individual productivity gains of 3.5-36.6% yield life cycle benefits with ROIs of 23-205%. Most of these studies do not identify if there is an energy penalty to individual control, which should be measured in the field. In their early installations of Personal Environmental Modules, Johnson Controls identified that the separation of broadband ambient conditioning from occupancy sensor controlled task air systems measurably reduced energy use in providing

thermal comfort in their Milwaukee offices (Lomonaco and Miller 1997). The CBPD research team is convinced that the separation of ambient and task conditioning with individual task controls of thermal conditions will yield both the energy and productivity benefits identified in studies.

Engineering for individual control of thermal conditions and dynamic thermal zone sizes is often achieved through the introduction of underfloor air systems or desktop air systems. In field and laboratory studies, underfloor air systems have proven to save 8-34% of conditioning energy given higher supply air temperatures, more effective delivery of air to the occupant, and reduced volume of conditioned space (ARTI/CBPD 2002) In other studies, both underfloor and desktop user-controllable/ task air systems have resulted in 11% higher individual productivity and 67-90% reduced churn costs. What these studies are clearly demonstrating is the complementary gains in indoor environmental quality and energy conservation, with very short payback periods.

Temperature control = Energy savings

Rose and Dozier 1997

In a 1997 simulation study, Rose and Dozier identify an average of 43% energy savings for HVAC systems with independent controls for each room, as compared to conventional large-zone HVAC systems.

2.2 Air Quality - Ventilation Control for Environmental Quality

The CBPD/ABSIC guidelines for high performance buildings argue for at least six guidelines for improving air quality in buildings, with the first two applicable to improving both thermal comfort and air quality:

- Decouple ventilation and thermal conditioning
- Engineer mixed-mode conditioning with natural ventilation (energy cost?)
- Engineer for dynamic ventilation zones
- Maximize OA ventilation rates and individual control (energy cost?)
- Improve site air quality, filtration and delivery (energy cost?)
- Innovate with user-responsive automation

Improving indoor air quality through ventilation innovation may indeed have an energy penalty. Given Existing HVAC systems, increasing outdoor air change rates certainly has an energy cost in very hot, cold, or humid climates. Increasing filtration can have increased energy cost, although re-engineering the effectiveness of the ventilation delivery 'path' could have an energy savings. Engineering mixed mode conditioning with natural ventilation can have a thermal energy cost if occupant feedback is not provided. Notwithstanding these potential costs, a range of design strategies have been shown to increase individual productivity through improvements in indoor air quality: Increasing outdoor air ventilation rates; improving ventilation effectiveness through task air systems or decoupled ventilation and thermal

*Floor-based Ventilation =
First Cost Savings + Energy Savings*

Milam 1992

In a 1992 simulation study of an Atlanta office building, Milam identifies \$0.43 per square foot savings in first cost and 1.55 kWh per square foot energy savings with underfloor air distribution systems, as compared to conventional ceiling-based air delivery systems.

conditioning; supporting natural ventilation with mixed mode HVAC systems; and source control by reducing indoor pollutants or improving filtration (Figure 5).

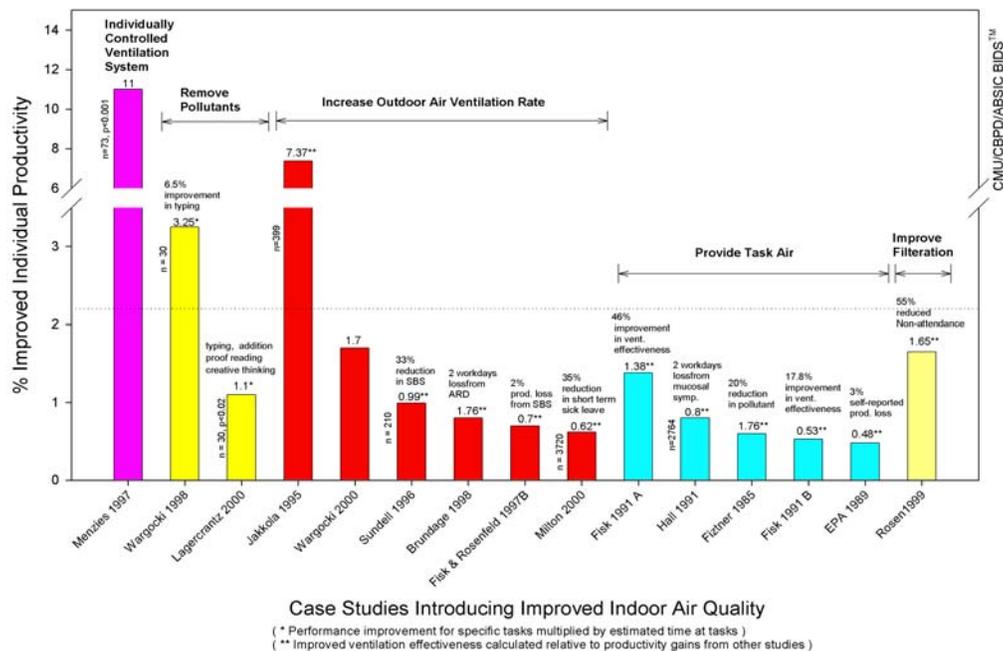


Figure 5 Improved Indoor Air Quality Increases Individual Productivity.

The CBPD team has identified 15 studies linking improved ventilation with gains in individual productivity. Six studies demonstrate 0.48-11% productivity gains with the provision of task air. Six studies demonstrate 0.62-7.37% productivity gains with the provision of increased outside air rates, and three studies demonstrate 1.1-3.25% increased productivity with the removal of primary pollutants.

While the productivity gains range between 0.6-7.4%, it is assumed in most of these studies that energy costs will increase in order to achieve the improved performance. Eto and Meyer (1988) estimate additional energy use at 8% for heating, 14% for cooling, and 1.5% for ventilation for an HVAC system with a ventilation rate of 10L/s per person rather than 2.5L/s per person. In developing the economic balance sheet, however, Fisk and Rosenfeld (1997) also identify improved health of workers given higher outdoor air rates, again at an energy penalty. Menzies (1997) shows an 11% increase in perceived productivity and a 20% decrease in work- or indoor air quality- related headache symptoms following the installation of a new ventilation system with individually controlled task air devices. Without pursuing engineering innovations such as high performance natural ventilation, improved economizer/heat recovery ventilation, or improved ventilation effectiveness (e.g. displacement ventilation and task air), however, the improved productivity and health through higher ventilation rates will come at an energy cost.

2.3 Lighting Control for Visual and Environmental Quality

The CBPD/ ABSIC guidelines for high performance buildings argue for at least five guidelines for improving lighting quality in buildings:

- Ensure daylighting without glare
- Separate task and ambient lighting (energy cost?)
- Specify high performance lighting assemblies
- Engineer for dynamic lighting zone sizing and individual control
- Innovate with user-responsive automation

While all of these guidelines may increase first cost, these guidelines should not create additional energy costs, and indeed have been shown to reduce lighting energy loads by 25-90% (Figure 6b). The one lighting design guideline that appears to have a potential energy cost is introduction of separate task and ambient lighting systems for visual quality. This apparent redundancy which increases installed lighting power, has actually proven to be an energy savings for two reasons: first, lower ambient lighting levels with occupancy controlled task lights measurably reduces overall light levels in unoccupied workstations (30% of the workday) and offers lower light levels for computer based tasks (another 30% of the workday) when task lights are turned off by the occupants. Secondly, the notion that one can provide adequate light levels from ceiling fixtures alone – at high light levels – has resulted in building managers and occupants almost universally purchasing secondary task lights to cope with the inevitable shadowing occurring in high density paneled workstations (resulting in 2-3 watts/square foot of installed lighting). Engineering separate task and ambient lighting systems at the outset can reduce this “actual” installed lighting load, and dramatically reduce operational energy use through occupant and daylight controls.

Notwithstanding the potential energy cost of this one guideline - separate task and ambient lighting - a range of lighting design strategies have been shown to increase individual productivity: glare-free, high-performance fixture design, including lamp, ballast and lens design; indirect-direct lighting; and improved lighting control systems (Figure 6a).

*Lighting Control =
Individual Productivity + Energy Savings*

Control Data Corp. / NLB 1988

In a 1988 before and after building case study of Control Data Corporation in Sunnyvale, California, the National Lighting Bureau identifies a 6% increase in worker productivity and a 65% decrease in lighting energy consumption following a lighting retrofit with high-efficiency fixtures and full-spectrum fluorescent lamps.

PP&L / Romm and Browning 1994

In a 1994 before and after building case study of the Pennsylvania Power and Light (PP&L) drafting office in Allentown, PA, Romm and Browning identify a 13.2% increase in productivity, a 25% reduction in absenteeism and 69% lighting energy savings following a lighting retrofit with parabolic louver fixtures and high-efficiency fluorescent lamps and ballasts.

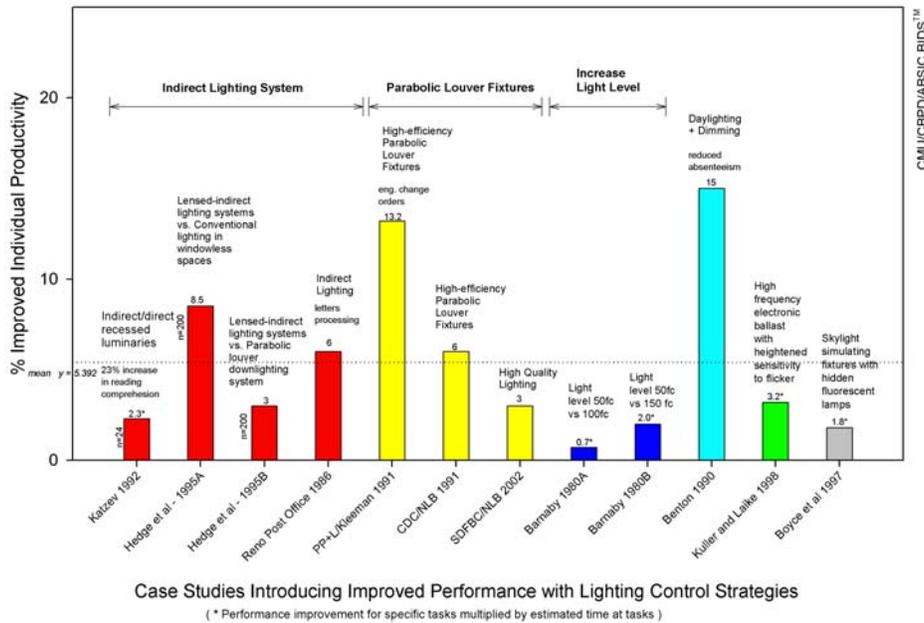


Figure 6a Lighting System Quality Increases Individual Productivity.

The CBPD team has identified 12 studies linking improved lighting design decisions with 0.7-23% gains in individual productivity. Four of these studies demonstrate 3-23% improved performance at a range of tasks given the introduction of indirect-direct lighting systems. Four studies identify 3-13.2% increases in individual performance resulting from higher quality fixtures – high performance electronic ballasts and parabolic louvers. Four studies identify the contributions of higher lighting levels and daylight simulating fixtures to 0.7-2% improvement in individual productivity at a range of tasks.

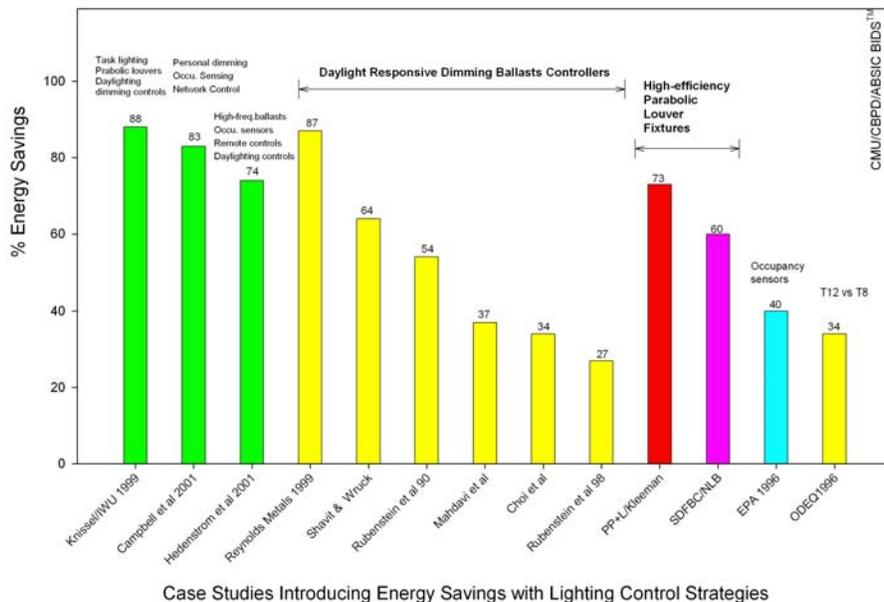


Figure 6b Lighting System Quality Reduces Energy Use.

The CBPD team has identified 13 studies linking improved lighting design decisions with lighting energy. Six of these studies demonstrate 27-87% energy savings through daylight responsive dimming. Four studies identify 40-88% energy savings through innovative control systems, often combining occupancy, daylight, and network control strategies. Three of the studies illustrate 34-73% energy savings from higher quality fixtures – high performance electronic ballasts, lamps and parabolic louvers.

A range of lighting design strategies have been shown to reduce annual lighting energy use by 27-88%, including: daylight responsive dimming ballasts; separate task and ambient lighting; high efficiency ballasts, lamps and fixture design; and improved lighting control systems (Figure 6b).

With 60-69% energy savings in addition to 3-13% productivity increases with high efficiency fixtures, lamps and ballast or with application of indirect lighting system, it is unclear why high performance lighting has not been retrofitted throughout the U.S. The potential for maintenance savings of \$.047/sq.ft per year as well (Knissel 1999) makes this lack of action even more surprising. One can only assume that it is the overall lack of life cycle bookkeeping relative to providing thermal, visual, and air quality to the building occupant that enables decision makers to continue to focus on first cost alone.

2.3 Access to the Natural Environment

'It is time to invent moral reasoning of a new and more powerful kind, to look to the very roots of motivation and understand why, in what circumstances and on which occasions we cherish and protect life.... We are human in good part because of the particular way we affiliate with other organisms..... To the extent that each person can feel like a naturalist, the old excitement of the untrammled world will be regained. I offer this as a formula of reenchancement to invigorate poetry and myth....' Biophilia E.O. Wilson, Ph.D.

The importance of individual access to the natural environment for health and productivity is a significant agenda for the building industry, with surprisingly little research underway in the science, engineering and design community. The CBPD/ ABSIC guidelines for high performance buildings argue for at least five guidelines relative to improving occupant access to the natural environment, several shared with improving thermal, visual and air quality:

Access to Natural Environment = Individual Productivity + Energy Savings

Lockheed 157 / Thayer 1995 | Romm and Browning 1994

In a 1995 building case study of Lockheed Building 157 in Sunnyvale, California, Thayer identifies 50% savings in lighting, cooling and ventilation energy and 15% reduced absenteeism due to the daylighting design, which integrates layout, orientation, window placement, type of glazing, light shelves, and ceilings.

Figueiro et al 2002

In a 2001 field study at a software development company, Figueiro et al identify a 15% increase in time spent on work tasks and a 35% decrease in electric lighting use for occupants of windowed offices, as compared to occupants in interior offices with no access to daylight, in winter months.

Four Oaks School / Nicklas and Bailey 1996

In a 1996 field case study of a new daylit elementary school in Johnston County, North Carolina, Nicklas and Bailey identify a 3% improvement in the performance of students in daylit classrooms as compared to the average performance of all students in the county, as well as a 60% overall energy use reduction in daylit schools over non-daylit schools.

- Ensure individual access to nature
- Ensure daylighting without glare
- Engineer natural ventilation and natural cooling
- Design for solar conditioning with overheating control
- Specify high performance, sustainably healthy building materials

While all of these guidelines may increase first cost, none of these guidelines should create any additional energy costs, and indeed should reduce energy loads by 10-80%. The importance of access to the natural environment to individual health and productivity is related to a number of design decisions: access to windows and view; daylighting through windows and skylights; natural ventilation and mixed-mode ventilation as well as passive cooling approaches from time-lag to radiant cooling; and directly accessible landscaped indoor and outdoor spaces - with measurable benefits in energy and productivity (Figure 7a and 7b).

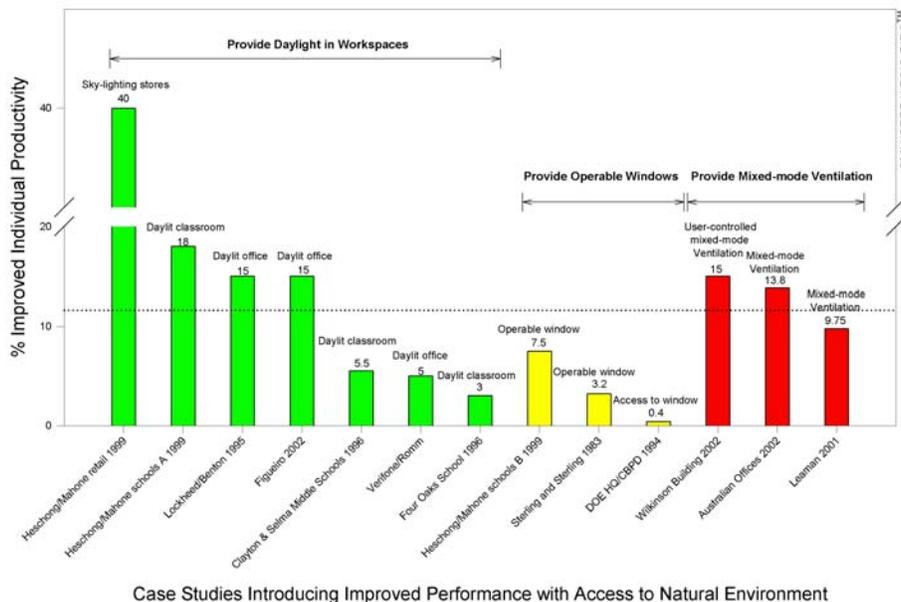


Figure 7a Access to the Natural Environment Increases Individual Productivity.

The CBPD team has identified thirteen studies linking improved access to the natural environment with gains in individual and organizational productivity. Seven of these studies have identified 3-18% increases in individual productivity (including student test results) and 40% increases in sales (an organizational productivity measure) as a result of the introduction of daylight in the workplace. Six studies further indicate that the addition of operable windows for thermal comfort, natural ventilation, or simply access to the outdoors, can impact productivity by 0.4-15%. The upper range of these productivity improvements, from 10-15% increased productivity, are achieved in mixed-mode buildings where operable windows are coordinated with mechanical air conditioning strategies.

Access to the natural environment, which has been linked to improvements in individual productivity, has also been demonstrated to reduce annual energy loads by 8.6-75% as a result of

a number of key design decisions: glare-controlled daylighting through windows and skylights; daylight control through dimming or movable louvers; natural ventilation and mixed-mode ventilation; and directly accessible outdoor landscaped workspaces (Figure 7b).

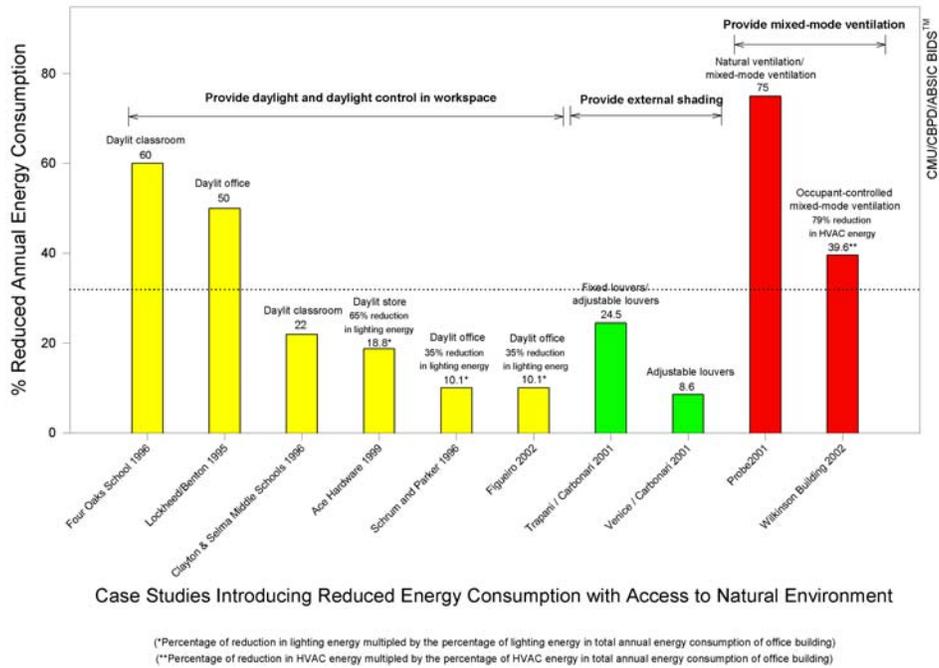


Figure 7b Access to the Natural Environment Reduces Energy Use.

The CBPD team has identified nine studies linking effectively designed daylighting and daylight control with 8.6-60% reductions in annual lighting energy consumption. Emerging studies on the effectiveness of mixed-mode HVAC, which balances natural ventilation and mechanical air conditioning, are demonstrating 39.6-75% reductions in annual HVAC energy consumption.

These laboratory and field studies have identified that individual productivity improvements of up to 18% can also yield energy savings of 22-75%. A handful of researchers have been completing studies that also link access to the natural environment with health, including Skov (1990) who has identified a 46% decrease in reported sick building syndrome (SBS) symptoms and a 30% decrease in reported work-related mucosal irritation in naturally ventilated buildings in Denmark. The importance of access to the natural environment to human health, productivity and now human safety in the face of rolling blackouts is an important area for ongoing laboratory and field studies.

3. CONCLUSION

The continued development of *e-BIDSTM* will depend on the building community's commitment to supporting laboratory and field studies that demonstrate the substantial business and environmental cost-benefits of a range of advanced and innovative building systems. The addition of a web-based life cycle decision support tool for the cost-benefit analysis of high performance building components, systems and whole building projects is critical to shifting

investments in buildings from first cost only to the quality comparisons that drive the automobile and the computing industries. In addition to identifying more laboratory and field studies, the e-BIDS effort will continue to pursue life cycle justifications that link gains in peak and annual energy efficiency to pollution benefits, waste management and renewability benefits, indoor environmental quality improvements, as well as gains in health and individual and organizational productivity.

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