Future Directions: Building Technologies and Design Tools

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Over the last fifteen years, improvements in the design and operation of commercial sector buildings have helped the nation slow the rate of energy growth. Initially, these savings were achieved by applying available technology and existing expertise. The need for even greater advances in energy efficiency in buildings remains, but is hampered by a lack of interest, lack of incentive, and lack of understanding of what is possible and what is required to achieve those advances. Fundamentally, energy efficiency remains low on the priority list of most Americans. If we are to make continued progress toward efficiency goals we therefore need strategies that link efficiency investments to other more desirable features and services, such as comfort and productivity.

We comment on the economic, political and social trends that influence building sector investment and development, creating both obstacles and opportunities. Large reductions in commercial sector use can be achieved by aggressively pursuing change in several directions. Development of new technology options, both components and building systems, will not only improve building energy efficiency but will contribute to more satisfying and productive work environments. We describe technical opportunities in the areas of building envelope systems, lighting systems, and HVAC systems, as well as integrated concepts for low energy buildings. Smart systems linked by intelligent controls is a recurring theme in each of these areas. Buildings are a process as well as a collection of components and buildings must therefore be viewed in terms of their life cycle in developing strategies for intervention. One of the most important and cost effective leveraging points is the design phase. We outline the tools and capabilities that will be needed to empower designers to successfully tackle the complex problems of integrating energy efficiency into cost effective building designs. Strategies to propagate a knowledge base from design to the operation and maintenance of buildings are also described.

Introduction

In the emerging national debate in 1992 about new priorities and directions for the country, stimulated in large part by election year rhetoric, little has been heard on the subject of energy policy. Traditional energy supplies remain plentiful and cheap, with the implicit expectation that this will continue. Growing concerns about environmental issues and global warming have yet to be integrated with energy issues into a coherent national or global agenda for action. The drinking glass labeled energy efficiency appears to be both half full and half empty. Efficient new technology has been developed and brought to market, and real energy savings have been achieved while the economy has continued to grow. Although study after study suggests that significant additional reductions in energy use can be produced cost effectively, the national commitment to capture such savings remains elusive. One bright spot in the last decade has been the development of significant utility interest and activity in integrated resource planning that has resulted in a flurry of new demand side management programs.

These programs are investing in energy efficiency to meet future growth in demand with minimal investment in traditional power plants. About one third of total energy use and about 2/3 of all electricity use is associated with buildings. The technical potential for savings in the building sector has been shown to be very large, in the range of 50-75%, but there is tremendous inertia in the building sector and there are numerous obstacles, disincentives, and risks involved in fundamentally changing energy use patterns in buildings. But, driven by economic and social forces, the building sector is in a state of continuous change, in planned and unplanned ways, and it behooves advocates of energy efficiency to aggressively develop and pursue strategies that will couple desired efficiency changes to broader building trends.

Motivation and Objectives

The future is determined by a confluence of large scale forces over which we have little direct influence and individual actions that collectively can be mobilized for real impact. Collective action can best be mobilized if there is a shared vision of where one is headed and at least a partial consensus on how one ought to get there. One of the most important factors, and one that is well within our control, is developing a vision of what we would like to see in future building developments. A detailed and definitive description is well beyond the scope of this paper but we attempt instead to begin to shape a view of key building trends and developments that might be consistent with a vision of a more energy efficient economy in the future. We hope to generate a dialogue on a series of interrelated issues and opportunities that together define both the obstacles and opportunities to change in the design, construction and operation of energy efficient buildings. Statements about current practice are intended as a starting point from which to explore future needs, trends, and developments. Given the breadth of the topic and the limitations of space the discussion will necessarily be incomplete and simplified. Our objectives are to develop shared insights into future development trends, issues, and problems for the design and operation of buildings in a manner that maximizes energy efficiency, minimizes adverse environmental impact, and improves health, safety and productivity in the work environment. We focus on the role of advanced design tools and selected building technologies, e.g., envelope, lighting, HVAC, and controls. We hope that through critical discussion and refinement of these scenarios we can begin to shape a collective plan for action that will help achieve the objectives and capture the vast potential energy efficiency savings in the building sector.

Context and Focus

Predictions about the future are notoriously dangerous and unreliable, and increasingly so as one ventures further in time from the present. This paper looks at selected current trends in technology and design, and speculates on where these trends could or should carry us through the end of the decade. This 5 to 10 year time frame is long enough to give us some leeway in fanciful speculation, but short enough that the majority of issues that will be important in that time frame are probably discernible today. Our focus is on commercial buildings, and many of our comments are made with office-type buildings in mind. However, much of our discussion is applicable to all commercial building types and some to residential buildings as well.

While our motivating interest is to examine the opportunities for a new generation of highly energy-efficient buildings, individual and collective private and public sector decisions will be made in an economic, social, and political context that extends well beyond the energy efficiency community or even the building sector. It is useful to briefly review some of the issues and forces that will drive change in the building sector over the next decade.

The commercial sector is on the downhill track of the economic roller coaster that saw rapid expansion in the early 1980s come screeching to halt in the latter part of the decade. A wide range of external forces influence commercial sector development. Corporate investment strategies, e.g., lease versus purchase, drive growth in the commercial sector and these in turn are influenced by the overall economic climate and by government tax policy, e.g., cost of capital, tax write-off policy. Demographics influence construction both in terms of an aging population, e.g., school versus hospital construction, home ownership trends, and in terms of changes in geographic trends, e.g., migration and population growth in the sunbelt. Lifestyle changes have already made major changes in all aspects of our lives: families with two working parents prefer 24 hour access to services and need new services such as daycare. The trend to telecommuting and the growing number of home offices could shift energy use patterns and load shape in the residential and commercial sectors for utilities. Videoconferencing could ultimately change the businessperson's love affair with the airplane. Telecommuting becomes even more advantageous for workers and employers as freeways and bridges become routinely gridlock, robbing hours of useful time. Even car phones and car faxes can't completely make up for the frustration of sitting in mile long parking lots. Traditional patterns of urban, suburban, and rural development will have to change drastically, along with the advent of better mass transit, before the commuting nightmares will disappear. As people struggle to improve their local quality of life, broader regional and national environmental issues are seen as increasingly important. Polls suggest that people are willing to pay more and make modest lifestyle changes to improve the "environment." The "Green" movement has the potential to make many changes in our lives if it can maintain a clarity of purpose and direction without being swallowed by technicalities or co-opted by Madison Avenue. Environmental issues are logically linked to most energy issues, providing a mutually supportive base for action. Market forces and building codes have stimulated some successful action in both areas. Regulated utilities operating under the enlightened policy of public utility commissions have become the most powerful force for change in the building efficiency market, influencing the owner/developer as well as manufacturers. Utilities may ultimately change their role from energy suppliers to energy service suppliers. In this role they might invest in efficiency equipment, e.g., lighting, HVAC on the owner side of the meter and lease back the equipment to the owner in a win-win situation for the owner and utility.

There are also important changes in progress on the "inside" of buildings that can change building design and practice over time. Companies are downsizing and rethinking their needs in terms of building stock. A more flexible company may have fewer employees and own fewer buildings so as to adjust more rapidly to future changes in the economy. The cost of employee turnover is now recognized to be very high and companies are becoming more concerned about the level of employee satisfaction with their work environment. This can be viewed as a proactive strategy to raise morale and productivity or a defensive response to limit the potential for lawsuits with respect to health impacts of the workplace. Of course it is also a very good common sense approach to maximizing profits by minimizing overall expenses including training, operating costs, health care benefits, etc.

Architects and engineers are constrained in what they can design and build by limitations in the marketplace in terms of available components and systems from building component manufacturers. U.S. manufacturers in the building sector do not invest heavily in R&D. This may put them at a competitive disadvantage to foreign competitors who are increasingly eyeing U.S. markets. Product development cycles need to be shortened to be able to respond better to changing customer needs, but regulations and aversion to risk conspire to keep them longer than they need to be. We can expect electronics to show up in virtually every product for the home. Smart components will need to be integrated into intelligent systems if their true performance potential is to be captured.

Finally the business of design and construction, and facilities management has not escaped the upheavals that have changed other sectors of the economy. Fees remain low and the complexity of the design process continues to increase. Design teams increasingly turn to consultants and experts to meet new needs, e.g., earthquake safety, handicapped access. The spectre of liability haunts designers and influences their decisions. Design offices, like other companies, have adopted electronic tools for the business end of their work, e.g., accounting, word processing. They are now making the shift to incorporate electronic tools into the creative design portion of their operations. More powerful computer-based tools are emerging, initially for each phase in the building life cycle. But eventually these tools will provide a continuous information management function throughout the building life cycle, which should provide benefits to owners, designers and occupants, and will ultimately contribute to efforts to improve the energy efficiency of building design and operation.

Buildings as Products

Overview

Buildings are large, complex entities that house populations of occupants with ever-changing needs. Most buildings are created as one-of-a-kind designs, where reinvention of the solution is the norm, as distinguished from industrial "mass production" that characterizes much of the rest of the built environment. Each design is an assemblage of components, subsystems and systems which are assembled on-site and ideally operate together in an efficient manner. Whatever the skill of the design team in pulling together a total design solution, the final building is a complex integrated system with many anticipated and unanticipated interactions. These interactions occur at many levels:

(a) components within a system interact, e.g., chiller and cooling tower

(b) systems interact with each other, e.g., lighting and HVAC

(c) external environmental effects, e.g., solar gain, drive the system in predictable and unpredictable ways

(d) internal occupant needs, e.g., comfort, productivity, impact the system

Control systems may provide some measure of de facto integration but it is typically a piecemeal integration at the system or subsystem level without building-wide control that links all major elements. Furthermore the control is not generally "intelligent" or adaptive, but rather hardwired to a small set of sensor inputs which limits its responsiveness.

If appliances or cars were designed this way we would likely be very unhappy with the lack of integration and its effect on overall "product" performance. Surprisingly, this does not seem to be a major issue in building design. We examine below some major building systems to explore the state of current design solutions, recent trends, and visions of a more energy-efficient, future building stock.

Building Envelope

Background. The design of the shell or envelope of buildings today involves decisions with numerous tradeoffs. The size, shape, massing, texture, color and overall appearance of the building skin is a compromise between cost, aesthetics, structure, site constraints, energy efficiency and numerous other influences. From an energy use perspective, the selection of the fenestration system (e.g., glazing, window, shading) is the most critical factor.

The historical evolution of fenestration and building skins has been heavily influenced by the changing relationship between what is desirable, what is technological achievable, and what is affordable. Since its emergence during the last century as a major building material, glass has evolved into a ubiquitous and versatile building design element, performing functions today that would have been unimaginable a few years ago. The optical clarity and transparency of glass that we take for granted is one of its most unique features. Windows keep out the cold wind and rain without blocking the view, but also perform many more complex functions, which require variable properties and tradeoffs between conflicting conditions. Fenestration systems that provide view must also provide visual privacy at other times and must sometimes become totally opaque (for audiovisual shows, for example). Transparent glass admits daylight, providing good color rendition and offsets electric lighting energy needs, but it can also create discomfort and disability glare conditions. The sun provides desirable warmth in winter but its heat is unwelcome in summer when it contributes to thermal discomfort and cooling energy requirements. And fenestration is a significant element in the appearance and aesthetics of a building from an exterior perspective, and a major determinant of the sense of spaciousness of building interiors.

There are three primary energy impacts of fenestration: winter heating loads, summer cooling energy and peak cooling loads, and daylighting. The first two impacts are addressed by HVAC system design and operation; the last represents an opportunity to minimize electric lighting loads. In addition to their energy impacts, conventional fenestration systems typically add to peak cooling load, which in turn increases chiller size and cost, HVAC system size and cost, and peak electric demand. Simply eliminating windows in buildings is not a viable option given owner preferences and developer market constraints. In fact, if occupant needs are deemed important, buildings would have even greater fenestration areas. It is not by accident that most executive offices are positioned near windows and clerks work in interior windowless cubicles. In Germany where union pressure has shaped office design policy, all workers must be provided access to window views. If these trends change American practice in the future, they could substantially influence the floor plan of buildings and the role of fenestration in these spaces.

These increased first costs and operating costs represent an inviting target for envelope design innovations that are capable of providing equal or better interior amenity at lower first cost than the equivalent HVAC system requirements or utility cost of providing additional demand. There are tremendous potentials for both new technology as well as better design and operations to substantially reduce the energy impacts of the building envelope. In fact, it appears to be technologically feasible to turn the envelope into a net source of energy for the building, as described below.

Envelope Performance Requirements--Heating. Converting fenestration performance in winter from a net heat loss to a net gain is conceptually a relatively simple task. Most commercial buildings have moderate to large internal gains, which are likely to grow in the future, and which reduce the overall net heating needs. With occupancy schedules that are normally less than 24 hours, the use of night setbacks and responsive HVAC controls contribute further to the reduction in net heating requirements. Code requirements for the opaque elements of commercial building envelopes are typically much lower than residential, and all can be met using cost effective technology that is available today. Commercial building window u-values today range from 3–7 W/m^2–K. Glazing u-values as low as 1.5 W/m^2–K are readily achievable with gas-filled, low-emissivity double glazing and overall window u-value (center glass plus glass edge plus frame) can reach these levels with improvements in frame u-value and/or further reductions in glazing u-value. Insulating glass units with u-values as low as .7 W/m^2–K are manufactured today using three glazing layers, multiple low-E coatings and gas fills.

It is well understood that south-facing windows provide substantial passive solar gain and that double glazing facing south provides net seasonal energy benefits in most northern climates since the solar gain exceeds the conductive losses. However, in even the coldest parts of the United States, north-facing "superwindows," i.e., $u < 1.3W/m^2$–K, will provide a net heating season benefit and thus outperform a highly insulated wall. Superwindows have such low conductive losses that even the diffuse gain from a northern, cloudy sky exceeds the typical conductive heat loss. While multiple glazed windows in commercial buildings may seem like overkill from the perspective of heat loss, and may have long economic paybacks, they provide an improved level of acoustic insulation which may be important in some buildings and they will improve thermal comfort immediately adjacent to large glass areas. Such systems have been used in commercial buildings in Europe, in combination with sun control options described below. At $100/sq. ft. floor area for construction costs, the ability to place workstations adjacent to windows and utilize every square foot of floor space provides an immediate offset to the extra costs of superwindows. Highly insulating glass technology has thus already made it possible to provide glass skins without a winter heat loss penalty. Future technical improvements are likely to occur in the area of reduced costs and reduced thermal bridging in the structural elements that support the glazing systems.

Envelope Performance Requirements--Cooling and Daylighting. Meeting the thermal and optical requirements to control cooling and capture daylighting potentials will be much more challenging. The properties of building envelopes of the future will have to be dynamic and more responsive to changing exterior environmental effects and interior occupancy needs. There are many building envelope options today that extend the intrinsic, static degree of control exhibited by glass alone. The traditional window sun control methods consist of coated or heat absorbing glass, drapes, shades, blinds and louver systems. Many of the operable shading systems are manually controlled, but some can be automatically controlled. The major sun control options are summarized below:

Low-transmittance glass includes both highly tinted absorbing glass and glass coated with a semitransparent, reflective metallic coating. These glazings help to reduce cooling loads, but usually limit available daylight, requiring that electric lights be on whenever the building is occupied. The emerging technology of spectrally selective glazings rejects the near-infrared portion of sunlight containing about 50% of the sun's energy and transmits the visible portion. This provides daylight with minimal associated total solar heat gain.

Interior sun control systems (shades, drapes, blinds, etc.) are well known and widely used. They are often selected on the basis of appearance and cost, with insufficient attention paid to solar control and daylight control solutions, and little or no attention paid to the likely user operation. Peak cooling loads are often calculated assuming the sun control is not used. Operable systems managed by occupants have the potential to perform well, if the users are conscientious. However, few HVAC engineers will stake their professional liability on the "hope" that occupants will use these systems properly. Limited studies and observed practice suggest that these systems are only rarely operated in an "energy-efficient" manner.

Exterior shading devices can be fixed, such as overhangs, fins, louvers, and shade screen materials, or can be operable. Exterior devices are almost always better at reducing solar heat gain than interior devices since the majority of the absorbed energy is typically rejected. Exterior systems shade the window from direct sun but often allow some view of the sky so that daylight can be admitted. In addition they scatter the incident solar beam so that diffused and attenuated direct sunlight is also introduced. Fixed solutions invariably represent an imperfect compromise between the conflicting requirements of sun control, daylight admittance, and glare control.

Motorized operable exterior/interior sun control systems should provide better performance than fixed systems. Operable systems can be manually or automatically controlled. Automatic controls with manual overrides would appear preferable, ensuring that the systems function properly to meet occupant needs at all times. Exterior operable sun control systems have been used successfully in Europe for some time and to some degree in Asia and are recently attracting attention in North America. They are relatively costly compared to standard interior treatments or any fixed glass type, but since they may allow reductions in cooling system sizing as well as permitting daylight utilization, they may be economically beneficial if all costs are accounted for. Some of the additional costs that have to be factored into these shading systems are servicing costs and problems with weathering of the outdoor systems. Motorized systems for interior shades and blinds are now commonly available although they are expensive and often lack sophisticated control systems. They can be operated with infrared controllers similar to the ubiquitous controls for home electronics. Operable shading systems should also provide improved thermal and visual comfort relative to most fixed shading solutions. While it is difficult to estimate the economic benefits of comfort directly, the cost of unhappy and uncomfortable office occupants is clearly large. The opportunities to link these technologies to HVAC system controls are discussed later. Specifiers continue to be concerned about the long term maintenance costs of these mechanically based systems.

Dynamic Envelopes and New Envelope Technology. The most difficult problem confronting a building designer in controlling solar gain and daylight is the tremendous variability in the environmental forces that impinge on the building exterior and the rapidly changing needs inside the building. For example, the intensity of sunlight varies on several time scales; by the seconds or minutes on a day with scattered clouds; by the hour as the sun follows its diurnal cycle; and over months as the seasons change. Since exterior daylight illuminance can vary by a factor of 10 to 20 during a day, from approximately 5000 lux (approx. 500 fc) under overcast sky to 100,000 lux (approx. 10,000 fc) in direct sun, controls to modulate light and heat must operate effectively over this wide dynamic range. Interior needs can change "rapidly" also. An office worker may need to simultaneously extract information from a document with small print (requiring 1000 lux) and then manipulate that data on a computer screen (requiring a low luminance environment).

Building envelopes of the future will have to be dynamic to respond to these varied needs. Complete control of sunlight to maximize energy and demand impacts implies control of the spectral content, the direction, and the intensity of transmitted light. Advanced coatings deposited directly on glass or plastic will provide the window systems of the future with the same sophisticated solar control that now requires mechanical devices, but with improved performance, reduced maintenance, lower cost, and longer lifetimes. The performance requirements for such ideal glazings are complex because of the multiple functions they must serve. Several control strategies may be used simultaneously to solve important performance issues:

Issue: Reduce Adverse Cooling Impacts

(1) Cooling energy

(2) Peak cooling loads and air conditioning system size

(3) Peak electric demand

(4) Thermal comfort

Approaches:

(a) Active modulation of transmittance, e.g., chromogenic films

(b) Passive rejection of solar gain, e.g., spectral and angular control

Issue: Increase Beneficial Impacts of Daylight

(1) Reduce lighting energy

(2) Reduce peak electric demand

(3) Simplify lighting control hardware

(4) Visual comfort

Approaches:

(a) Spatial and spectral control in perimeter zone, e.g., spectral and angle selective transmittance

(b) Glare control, e.g., chromogenic films

(c) Daylight intensity control, e.g., chromogenic films

(d) Collect and distribute light to core of building, e.g., concentrators and light guide systems

The most important control function is control of the intensity of transmitted solar energy. An international race is in progress to perfect "smart windows," using chromogenic materials which allow glazing transmittance to be controlled. Examples of such materials are available today for other applications: photochromic sunglasses switch as a function of light intensity; nematic liquid crystal temperature indicators change optical properties in response to temperature changes, and twisted nematic liquid crystal watch displays switch from transparent to reflective as each digit changes. It is possible to produce chromogenic materials having transmittance properties that change from clear to reflective or absorptive as a function of exterior climate conditions such as sunlight intensity or temperature, or to use an electrical control system that changes transmittance as a function of climate and building conditions. Light-sensitive (photochromic), heat-sensitive (thermochromic), and electrically activated (electrochromic and dispersed liquid crystal) devices will respond differently in a building to different environmental forces. This will result in different effects on lighting energy requirements and cooling energy requirements as illustrated schematically in Figure 1. Relative requirements for cooling and lighting are shown for four types of conventional glazings and for three types of chromogenic glazings. The lowest total energy consumers are the electrochromics shown in the lower left. These electrically controlled coatings can be actively controlled throughout the year to minimize both lighting and cooling, and thus appear to be the technology of choice. Photochromics have low lighting energy requirements since they respond to light but may have higher cooling loads. Conversely thermochromics could be selected to respond properly to minimize cooling but may not provide large lighting savings.

Electrochromic coatings will provide large reductions in electric energy use in commercial buildings since they can reduce both cooling and lighting needs. Energy simulation studies in hot climates show 60% cooling and lighting energy savings in building perimeter zones, as well as

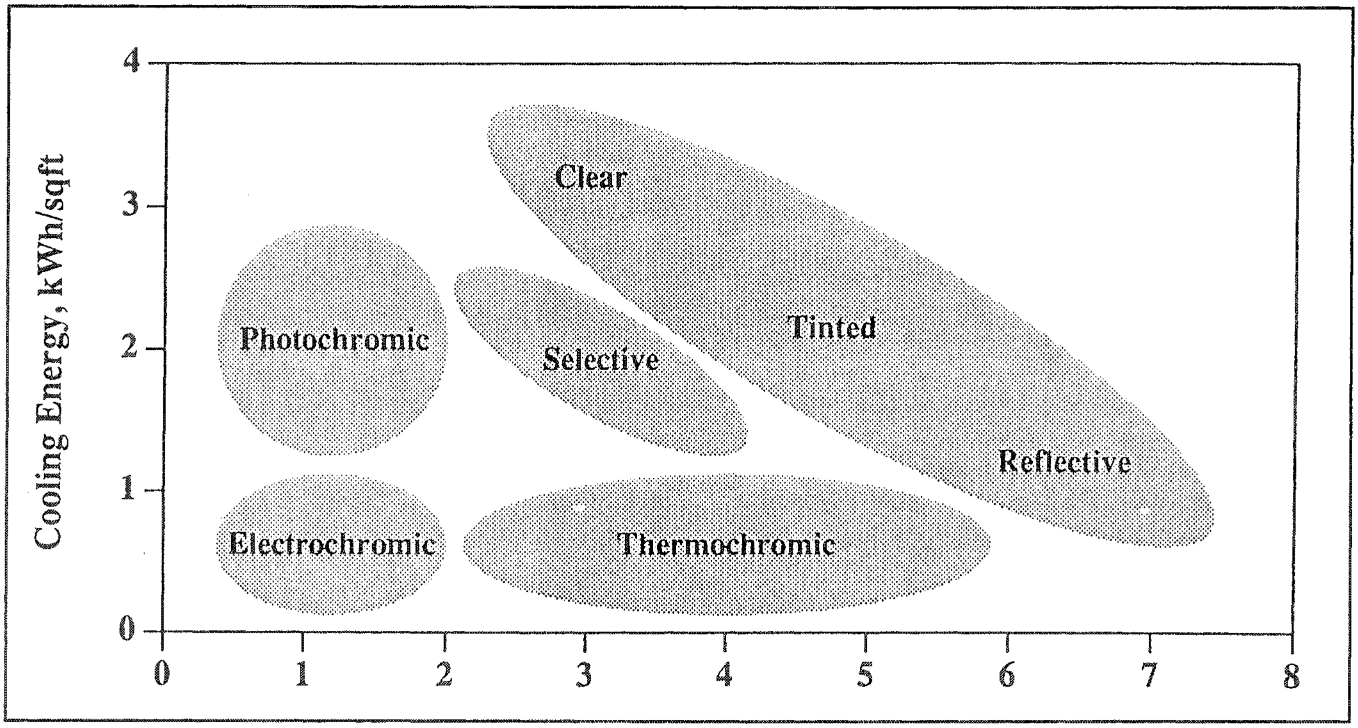

Figure 1. Electric Lighting Energy, kWh/sq ft

50% reductions in peak electric demand. Although these materials are 3-5 years from commercial availability, field tests of early prototypes have already showed 55% savings in peak window cooling loads compared to conventional tinted glazings. Simulation results suggest that electrochromic coatings will make it possible to specify windows of any size, without a comfort or energy penalty.

This technology is likely to be a market winner because it provides a wide range of benefits in addition to its energy performance. Privacy, glare control and improved thermal comfort will be important to occupants. Electric demand control will be important to utilities. The dynamism, and initially the novelty, of the chameleon-like building facade will appeal to designers and to owners, who will also benefit from the energy and demand savings. Reduced peak cooling loads should allow chillers and HVAC systems to be downsized, with the resulting savings offsetting 10-20% of the first cost of smart window systems. The ability to link the smart window controls to a building-wide, automated energy management control system should help convince engineers that chillers can be safely downsized, once the smart window technology is successfully demonstrated on "someone else's" building.

Electrochromic windows will provide excellent glare control which should improve the acceptance of daylighting strategies with large windows. But conventional windows and shading devices can use diffuse skylight to provide adequate daylight only within fifteen feet of the building perimeter and are not very effective in moving light deeper into buildings. A single square foot of window area in direct sunlight admits enough daylight to light over 150 square feet of floor area in an office building, if it could be efficiently redirected. Historically this problem was addressed with prismatic glass blocks which redirect light toward the ceiling in the back of the space. But glass blocks have many practical and performance limitations and are not widely used today. There has been much architectural interest in light shelves over the past 15 years as design solutions to redirect light deeper into rooms. However conventional flat or curved, painted light shelves have also not proven to be consistently good performers.

The ideal daylighting device would efficiently redirect light from any sun position to a location on the ceiling at the back of a deep room, without producing glare. There are many newer reflective, refractive, and diffractive optical technologies that could provide greatly enhanced control of transmitted daylight, although not reaching the ideal limit. Thin prismatic plastic films can be laminated to window surfaces to refract light. Other refractive glazing materials have been designed to provide improved light control. Reflective prismatic films can make a flat surfaces behave optically as if it was a curved shapes to allow better control of the sun over a range of seasonal incidence angles. Although the basic principles of these reflective and refractive optics have been known for years, there are new opportunities made possible by new manufacturing technology for low cost fabrication of precision optical surfaces in polymers. An additional option now under development is the use of diffractive holographic glazings. Holographic gratings can be designed to selectively and preferentially redirect light from a specific set of incident sun angles to a limited range of output angles with moderately high efficiency.

How might these be used in a dynamic building envelope with large glazed areas in a climate where both heating and cooling are required? Imagine an all glass facade split between a lower vision window and an upper daylighting window. Both windows incorporate superwindow technology to effectively eliminate heat loss. The lower vision window uses a spectrally selective glazing with an electrochromic coating that can be modulated between 70% and 5% visible transmittance. A light shelf separates the upper and lower window (providing some shading for the lower window), and has an upper electro-optical surface which is also controlled to provide additional directional light control for the upper window. The upper window uses a similar selective/electrochromic glazing but with a separate control strategy. Both windows are linked to a smart control system that assesses the following factors before setting the transmittance of each window and the state of the light shelf reflective coating: current climate conditions, projected future climate conditions, current HVAC system operating requirements and building demand profile, time of use rates, and the occupancy and tasks in the adjacent space as determined by activity on desktop PCs, number of occupants, and any specific occupant preferences and requests. The same control system sends signals to the dimmable lighting controls and the local HVAC system. Depending upon the overall building load profile such a system should be able to significantly reduce lighting loads (both direct lighting and indirect cooling load), and envelope cooling loads, leaving only the internal equipment loads and conditioned air loads.

Large Scale Climate Envelopes. Buckminster Fuller noted that when viewed from a distance, the urban skyline looked like a good heat exchanger with a relatively large ratio of exposed building surface to the land or floor area available. He proposed covering small cities or portions of large cities with a semitransparent geodesic dome, but the scheme never advanced beyond the sketch stage. Others however have built fabric structures to enclose relatively large spaces, e.g., football and other sports arenas. These structures, held in place by air pressure or cable tension structures, are very efficient structural solutions for spanning very large distances and enclosing large areas and volumes cost effectively. The Teflon coated fiberglass skins have a relatively good track record for durability and can be expected to last 20-30 years. One of the weak points of these design approaches that has limited their use largely to spaces used intermittently, such as sports halls, has been the thermal integrity of the envelope which consisted of a low transmission (typically 4%) single layer fabric. In cold climates occasionally a second fabric layer is added for thermal insulation and more recently fibrous insulation is added between the fabric layers. However, variants of the optical and thermal technologies discussed above should make it possible to provide high thermal insulation levels in the skin and to provide dynamic control of solar transmittance using "smart window" coatings.

It is useful to rethink building design if you have the technology to cover a city block (or four blocks or sixteen blocks) with a large climate modulating envelope. Such a climate control envelope would effectively eliminate wind and rain as a determinant of building skin design, and, with proper control, should be an effective climate modulator, allowing some control of average temperature, and greatly reducing the range of temperature swing in all seasons. Buildings beneath the skin would then have to provide structure, privacy, security, and acoustic control, but many of the conventional climate control functions of the individual building would be changed. Such a design would also lead to other opportunities and constraints. For example, vehicle movement within such a structure would have to be limited to low emission vehicles.

The concepts are far from fanciful. A multiacre fabric structure was built in Saudi Arabia and serves effectively as a sun shield at a major airport. Concepts for enclosed cities in Alaska have been seriously studied. The Government Services Administration (GSA) commissioned a study to examine how office buildings might be designed under such a protective umbrella. A series of ever larger and more sophisticated sports stadium and other individual fabric covered buildings and portions of buildings continue to be erected. The potentials of new dynamic materials for optical and thermal control add to the likelihood that such a large space enclosure structure can be successfully built.

Lighting

Background. Lighting has always been a visual and visible symbol of energy use and misuse. It is often the single largest electricity cost in commercial buildings today. It influences electricity consumption directly and indirectly since there is often a cooling load associated with lighting energy use. It is a component of peak electric demand, although the impact is generally flat throughout the occupied period of the day. To the building occupant, lighting makes it possible to carry out the functional tasks he or she is paid to do, at the same time it creates a visual environment that forms the background for completing those tasks. In the context of seeking energy efficient solutions for lighting, some have lost sight of the fact that the quality of the background visual work environment is just as important as the quantities of light delivered to the task. From an architectural design perspective, lighting defines the appearance of the building as a whole and within each of its spaces.

High tech hardware solutions to energy efficient lighting that ignore these "non-energy" realities have not been very successful, if the real goal is defined as having satisfied and motivated building occupants efficiently completing their assigned tasks. A very narrow technical solution would provide each employee with a miner's head lamp and night vision goggles to effectively eliminate the electric lighting loads in buildings. There is no single "best" lighting solution any more than there is a single "best" window design. There have been great advances in development of more efficient lighting components over the past 15 years, particularly in the area of improved lamps and ballasts. But there has been less success in fully integrating these components into lighting systems and still less in tying these lighting systems into broader building systems. Part of the problem is an engineering problem, complicated by the structure of the lighting industry and the nature of the lighting design and engineering profession. An equally important problem is our imperfect understanding of very basic psychophysical aspects of human response to light. Fundamental work in this area is still in progress to determine how the human eye responds to glare and what constitutes an acceptable glare-free environment. Changing tasks have kept researchers busy over the past decade as 30 years of studies based on reading fifth carbon copies have been supplanted by new studies on the visibility of computer screens. Even the most fundamental model of the spectral response of the eye has been challenged based on recent research findings. It is interesting to speculate on the potential for havoc in the thermal engineering community if it was faced with the possibility of a large change in the basic definition of a Btu.

From a long list of interesting challenges and opportunities we focus on trends and directions in lighting design and technology that involve some degree of integration within the lighting systems or between the lighting systems and other building systems.

Lighting Controls. In the not-very-distant past the primary form of lighting control in buildings was a circuit breaker hidden in an electrical closet. In some cases even these were not used since operating lights 24 hours per day cost very little and there was a widespread misconception that switching lamps off seriously shortened their life. Progress over the last decade has occured both in the technology of controls and the shift in standard design practice. Accessible lighting controls, e.g., on-off switches, are now prescribed by most energy codes and are often circuited to provide two light levels.

A wide range of new control options can now be specified beyond the minimum on-off switching requirements. Lighting design is changing from a paradigm that favored constancy and uniformity to a new approach that matches the spatial and temporal pattern of lighting to the needs based on occupancy and task requirements. This has major ramifications for the design and selection of lighting systems.

If specific spaces are unoccupied, there is generally no need to have lighting, unless the space serves a secondary function such as circulation. Occupancy controls can be based upon time clocks if the occupancy pattern is completely predictable, or by systems that sense for the presence of people, using either passive infrared detectors or active ultrasonic detectors. Much of this technology originated with security systems and has been adapted for use with lighting controls. The sensitivity of sensors can generally be adjusted so as to operate when they should with a minimum of false triggering. A given space may be served by one or more light sources and the response of each source to the sensor signal is generally based on a hard wired linkage, although sensor sensitivity and time delays can be adjusted.

Light level sensors are used to switch or dim electric lights in response to the presence of daylight, and to account for lumen depreciation, the change in lamp and fixture output over time. Lighting systems are designed to meet requirements just before the lamps are replaced. Since there is some loss of light as lamps age and as fixtures accumulate dust and dirt, the system provides more light than is needed when the components are new. Light level sensors linked to dimming ballasts can reduce the power and light output of the system when it has new lamps and clean fixtures, and then adjust these levels as the system ages. The same type of sensors can respond to daylight, either turning the system off if the daylighting level exceeds illuminance requirements or dimming or partially switching some lamps off if daylight is present but inadequate. Sensor response depends upon the design of the detector system, its location in the space, its field of view and the nature of the daylighting system. Field experience suggests that there is a need to improve the operation of these sensors and controls.

In future buildings, new lighting sensors and controls will be needed to squeeze additional performance from lighting systems, at lower cost and with greater occupant satisfaction. Multiple types of sensors would send signals to a controller that would then decide how each fixture should be operated at that time based on priorities and send the control signals to the fixtures to respond appropriately. Today's hardwired sensor-fixture systems would be replaced with a more flexible system in which the central controller can selectively address any fixture. If office walls are moved and a fixture is now located in a different space a simple software fix accommodates the change. Since visual tasks are constantly changing the lighting controls should be readily reprogrammable to respond to these changing needs. The occupants needs must be communicated effectively to the control system. Controls might "learn" the occupants desired response patterns using neural network software. Lighting might also be readily controlled with a utility program on a desktop computer, via a touch tone phone system, a remote wireless controller, or by voice command.

There is an additional level of control integration involved in linking lighting to security and energy management systems. A building wide demand controller might ask all lighting units to lower their power consumption by 10% for an hour to get through a period of peak demand without exceeding a preset level. A smart lighting system could provide this "spinning reserve" within the building with little or no loss of amenity or performance.

Controls for good lighting would balance the functional and aesthetics aspects of work in an office environment. There may also be conflicts between occupant preferences and the most energy efficient operation of the lighting systems. The power of truly flexible and responsive systems would be the ability to accommodate a wide range of needs, without dictating a priori how those needs would be met.

Light Fixtures. Electricity is transformed into light by ballasts and lamps but it is the lighting fixture or luminaire and the space itself that "delivers" the light to the task and creates the overall luminous environment. Less attention has been paid to the design and improvement of luminaires than to other lighting hardware components. Fixtures can modify the color and distribution of luminous flux as it leaves the source. The room and its furnishings act as "fixture" in the sense that they also absorb, reflect, and redirect light. Design decisions regarding room geometry, e.g., ceiling height, and surface reflectances can have a major influence on the light distribution in a space.

Innovation in fixture design can occur at several different levels. The recent adaptation of recessed fixtures to accommodate compact fluorescent (CFL) sources in place of incandescent results in the CFLs operating at a higher than desired temperature with a resultant loss in light output and efficiency. Relatively simple changes in geometry, the use of convective venting, and heat sinks can improve performance by 10-20%. Most fixtures are static in design. The smart optical materials described above for use in windows could be adapted for use in fixtures where a small electric current could switch a clear element to a reflective element and thus change the resultant light distribution. Fixtures that use sources with concentrating or diverging reflectors or refractors will change output properties as the spacing between source and surface changes. Such spacing changes could be actuated by a variety of passive or active elements. The surface properties of the room itself could become dynamic, changing reflectance and/or hue to create different light levels or moods. Technology borrowed from theatrical design could be used to control the throw of light across spaces from efficient centralized sources. Other optical elements such as light guides or light pipes can also transmit light very efficiently over room sized spaces. The opportunities to improve the control over light distribution are numerous. The major constraints have been cost. Interestingly the continued advances in source efficiency make it more difficult to justify additional investment in fixture technology to save energy. However, coupling improvements in the qualitative aspects of lighting with efficiency improvements is the best strategy for moving these new concepts into practice.

HVAC Systems

The most common perspective on improving HVAC efficiency is probably the trend toward higher heating and cooling equipment component efficiencies. However there are technical limits to improving component efficiency and there are many additional issues and trends that are reshaping HVAC design and operation. As expected, these pose opportunities that can be explored and problems that must be addressed.

Shift From Peak Design-Based to Optimization-Based with Variable Constraints. Traditional HVAC design methods produce systems that are designed to carry the peak cooling or heating load for all but a few hours of the year. Although it is important that an HVAC system meets peak cooling and heating loads oversizing can produce systems that are inefficient since most components operate less efficiently at part load conditions. The HVAC designer is thus faced with a dilemma, oversize and play it safe, or downsize a system and take a chance that somewhere down the road the system may not be able to meet the prevailing loads which could cause litigation and possibly an expensive redesign.

New design procedures will need to be developed that will allow the designer, who is implementing the desire of the owner, to efficiently choose a system that will maximize the intended benefits: comfort, IAQ, lighting quality; minimize the costs: energy costs, purchase price, etc., and meet peak cooling and heating loads without having oversized systems. Shifting toward such a procedure would require a fundamental change in the way building HVAC systems are designed because the prevailing peak-design procedures require one calculation for the worst case condition. In an optimization-based approach the designer would begin with the same basic building description and add information about the importance of benefits and costs to produce an entire spectrum of possible design choices that can then be tailored to meet the client's changing needs. This could all be accomplished in near-real-time during a presentation as different options are brought-up and explored.

Such a procedure is likely to gain more acceptance today for several reasons. First, with the ever increasing use of variable-volume and variable flow systems the penalty for oversizing has been substantially reduced. This is because VAV is inherently dynamic and can respond to a varying load Second, better insulated buildings and buildings with thermal storage can reduce the magnitude of the peak load upon a system. Finally, it is conceivable that improved control systems will be able to anticipate severe conditions and ramp-up heating or cooling to prepare for them in advance by precooling or preheating conditioned spaces.

Delivering the BTUs and Indoor Air Quality (IAQ). Unfortunately, there is some evidence that variable-volume systems, if not carefully designed can lead to problems with IAQ in a building. Although proper attention to detail should prevent this from occurring in the first place, some building owners have found out the hard way that energy efficient VAV can exacerbate hidden IAQ problems. HVAC designers are having to rethink control strategies that traditionally allowed for a pre-determined amount of ventilation air regardless of varying rates at which the air is delivered to a space. Some newer systems are beginning to appear that actually allow for CO^2-based ventilation control--a true variable ventilation, variable air volume system. Unfortunately, these systems require expensive, and difficult-to-calibrate, indoor-outdoor continuous CO^2 monitoring.

Variable flow is also presenting a new family of problems for building operators--measurements of low-flow rates. As systems begin to use lower air and liquid flow rates the measurement of these flow rates, for control and monitoring purposes, is becoming more important. Unfortunately, most affordable liquid flow sensors cease to function properly at velocities of 1/2 to 3 feet per second which makes thermal (Btu) measurements almost impossible without expensive sensors. Accurate metering and control of air flow below 500 feet per minute also becomes problematic and expensive. Significant effort will be needed to create affordable, accurate, easy-to-calibrate, low-flow air and liquid sensors.

Design procedures for diffusers will also need some revisiting. Traditional methods which rely on manufacturer's data at one or more flow rates fall short of providing an accurate picture of dispersion under conditions of varying flow and pressure. Advances in the field of computational fluid dynamics will certainly provide some new answers and may ultimately provide some new tools for designers.

Personal Comfort Systems. Some HVAC designers are promoting personal comfort systems as the minimum energy and maximum comfort choice. Such systems seek to put individual control (versus one thermostat for several offices) into the hands of the building occupant. The advantage of such systems is in their infinite flexibility and potential minimum energy use. Unfortunately, the disadvantage is in their higher first costs and possible higher maintenance costs. For example, instead of one filter-bank and cold deck for 10,000 ft^2, one may now have 100 filters and cooling coils to maintain with an equal number of control valves, etc. It is not clear at this time whether these systems deliver improved comfort and better energy efficiency or whether they deliver better performance at higher maintenance and energy costs. There are several heavily instrumented demonstration programs now underway that should help assess the real costs and benefits of this approach.

Owning or Leasing HVAC Systems. Who should own the HVAC system of the future? Should a building's HVAC system be thought of as an extension of a service that a utility provides? Ownership of equipment in a building by a utility (or phone company) is nothing new. Consider who owns the transformer in many buildings. Sometimes it is the building owner. Sometimes it is the utility. What about the utility meter? Could a building's

HVAC system be thought of as an extension of the utility grid to provide a "conditioned" form of energy in the same sense that cable TV operators provide a conditioned entertainment signal. Quite possibly such systems would look completely different because utilities are used to designing for different constraints, namely: long-life, low maintenance, high efficiency, etc.

Perhaps HVAC systems could simply be leased like PBX phone systems are. Although unthinkable 10 years ago, there are several developments that are making this possible today. First, EMCS protocols are beginning to pave the way for one control system in a building that different vendors can plug into. Second, most existing buildings that do not have efficient HVAC systems will either need to be replaced or retrofit in the next 10-20 years. Since a significant number of these same buildings were built to minimum specifications and are already suffering from 10% to 20% vacancy rates owners will be hard pressed to make an investment solely for energy efficiency. However, if the financial wherewithal of the local utility and energy service company can be tapped, the idea of investing in an efficient HVAC system for a customer becomes an attractive opportunity for both the customer and the investor.

Low Maintenance HVAC Systems. During the life of a building the maintenance costs of an HVAC often equal or exceed the costs spent on energy. In certain applications, for example in fast-food restaurants, customer comfort and minimum down time are far more important than energy costs. Systematic research that looks into what breaks and why is needed to better understand how to design, build and maintain HVAC systems. On-line diagnostics will also play an important role in the future. For example, can a temperature-based diagnostic system be developed for packaged air-conditioners that will alert the building operator or service contractor to fouled coils or low refrigerant charge?

In larger buildings perhaps HVAC systems can be routinely maintained by robots. Although this seems far-fetched, many of the maintenance tasks that are performed on an HVAC system could be automated, for example changing filters or inspecting ductwork. In larger mechanical rooms, HVAC manufacturers might simply supply a maintenance robot that is preprogrammed to perform such tasks on all the air handlers in the mechanical room.

Savings in Existing Buildings. It is critical to directly measure energy use in buildings to make sure that anticipated savings occur. With only 1% to 2% of the building stock being replaced each year many designers find themselves redesigning more often than evaluating new design. Many buildings are built with HVAC systems that cannot be easily retrofitted. Early results from the Texas Loan STAR program have already documented several case studies where this was true. In almost every case anticipated savings from HVAC retrofits must be measured for some period of time to make sure that they are occurring as planned.

Likewise, measurements can provide a means to give building operators (and architects/engineers) continuous feedback about how a building is operating. Often, such feedback can help identify and remedy O&M problems that exist in buildings simply because the operators cannot assess their day to day actions. In many instances, when the building owners and operators know that the savings are going to be measured their reluctance to performing the retrofit disappears, a form of quality control.

Unfortunately some savings calculations cannot be easily verified by field measurements, hence the need to revisit the way that savings calculations are performed. Many HVAC energy audits use rules-of-thumb, or annual savings estimates that cannot be easily measured once the retrofit is installed because one year or more of contiguous data are required to make an assessment.

New HVAC Markets. With a large portion of the third world in need of adequate, affordable housing, perhaps it is time to revisit factory-built modular housing that can be shipped and quickly assembled on-site with a minimum of labor. The idea for such a system is not new, in fact prepackaged housing was used during colonial times in Australia, and to a lesser extent in this country. Japan and Europe are already well established in this field where they've shown that modular housing can be efficient, attractive and exportable. For the HVAC designer, this will mean a radical departure in the way that an HVAC system is laid out and designed--with an emphasis on flexibility, modularity, expandability, and quick assembly in the field.

Such modular housing could be just the ticket in this country's inner-cities that are in need of affordable, durable, and efficient housing for the poor. The HVAC systems in such structures would need to be designed differently than HVAC system in most residences because they would need to be almost maintenance-free, vandal-proof, inexpensive and most importantly, efficient. There is a demonstrated need for such systems because many of the nation's poor are the least able to afford new efficient technologies that could be used to prevent tax payer subsidies from being wasted year after year on inefficient energy use.

HVAC Controls. Is there a need for cellular HVAC comfort systems? In such systems each person would be issued an ID badge that has electronically inscribed their comfort preference. As they pass through a building during the day HVAC system would "sense" their presence and adjust systems for their desired comfort level. If more than one person were in a room a mean predicted vote could be calculated, and/or priority levels assigned to accommodate different comfort levels. Systems would then revert back to some preset minimum comfort level when unoccupied, or simply turn off; turning-on again when the entrance door sensor IDs the arrival of their normal occupant to preheat/cool as the occupant makes their way to the office.

Low Energy, Whole Building Systems

Decreasing world energy supplies and increasing energy demand, especially in developing countries and in newly free eastern European countries can only help to increase upward pressure on energy prices. Environmental pressures are also likely to place added emphasis on energy efficiency as a solution to a host of interrelated environmental problems that are part of the bigger issue of sustainable development. It may again be time to begin investigating building systems that rely wholly, or in part, on alternative energy strategies coupled with the best efficiency options--"zero emission buildings" to steal a phrase from the auto industry. Ongoing developments in many fields may now make this possible, specifically, photovoltaics, optical materials for thermal and lighting control, advanced heat pipes, high-efficiency absorption cooling, improved adsorption dehumidification, and of course, the ever present microprocessor.

For example, perhaps an HVAC system could be tasked to circulate only the necessary ventilation air leaving the heating and cooling of a building to an integrated building envelope system discussed earlier with appropriate dynamic thermal control. These envelope systems could virtually eliminate heating and could reduce cooling loads by 80-90% relative to conventional windows, with most of the heat gain associated with daylight. Such systems could also act as environmentally-driven heat-pumps that efficiently pump unwanted heat from the interior through the envelope.

Lighting needs would be provided by a high efficiency lighting system using the most efficient sources, smart fixtures that adapt to provide light where it is needed, and associated controls that only provide light when it is needed. Electric light would be used only a small number of hours per year or for special functions since the building floor plan would allow daylighting in most of the occupied spaces. Even spaces remote from the perimeter or roof would receive daylight from solar "light pipes," which efficiently duct light 150 feet from rooftop collectors to the point of use.

Despite the growing use of new types of office equipment and their increased functionality, chip technology would keep up, requiring only a fraction of what today's equipment requires for equivalent use. High density erasable optical storage and improved displays would greatly reduce the need for paper copies, freeing valuable floor area formerly occupied by file cabinets. The new office equipment would provide video conferencing and electronic/video mail delivery, eliminating some fraction of energy use associated with air travel and overnight parcel delivery, providing additional energy savings outside the building. Such a building would be able to operate on net electric requirements in the 0.5–1.0 Watt per square foot range--during occupied hours!

The residual office equipment requirements as well as power for cooling systems could be provided by photo voltaic arrays that are integrated into curtain walls, shading, and roofing elements. PV arrays would feed electricity to thermoelectric heat pipes, or possibly a close-coupled solar absorption cooling system (no moving parts) driven by solar collectors embedded in the building's roofing. By design and operation, buildings would be intrinsically "stable" allowing them to "coast" through the weekend with the heating (and cooling) systems completely turned-off in both severe northern and southern climates. In northern climates this would mean careful attention to freeze proofing, e.g., where water pipes are placed. In southern climates a small (alternative energy powered) system could be left running to partially cool and mostly dry the air in the building--thus preventing mold and mildew growth. Both types of buildings could be assigned special rates from the utilities for their interruptable potential.

Buildings as Process

In the previous section we focused on innovative technology as a force for change that could lead to a new generation of more energy efficient buildings. Major opportunities to improve the energy efficiency of buildings can also emerge from a reexamination of the process by which buildings are designed, constructed, operated and maintained. As noted above, the major elements in the building life cycle are fragmented and disconnected. Although the physical building operates as an integrated system (by default, if not by intent at times), the building life cycle process is not well integrated. Managing the design of a building and then its subsequent construction and operation is an information-intensive process. Of the vast amount of knowledge that is created and manipulated in the course of the building life cycle, much is lost or buried and never used in subsequent stages in the life cycle. This is a result of the nature of the process, the number of different actors involved, the long time periods over which buildings operate, and the lack of a tradition of documentation that is preserved, transmitted and updated in a form useful to those needing it at any point in the cycle.

Buildings that Fly

Can this process be improved upon? Are there activities in other sectors of the economy that might serve as partial models for alternative approaches? It is instructive to compare the building process to the design, assembly and operation of other large structures with sophisticated operating systems, such as aircraft. (It may also be instructive to examine other subjects such as automobile or ship design for similarities and differences--we leave this to the reader). While smaller buildings are often designed from something resembling a "kit-of-parts," most large buildings are one-of-a-kind structures that are reinvented each time they are designed and built. Relative to buildings there are a number of significant differences in the development of a new commercial airliner.

With a new airplane, even before design begins the manufacturer works closely with the potential clients to define the functionality and operating costs of the vehicle, and delivery schedules. Contracts often specify penalties for not meeting or incentives for exceeding these performance criteria. The design phase for a new airplane is much longer than for buildings. It includes creation of a series of full scale mockups that are used to refine both the final functionality of the plane from the perspective of the user as well as mockups that allow assembly problems to be worked out while still in design. Maintenance issues are addressed in the mockups, such as access to parts and systems that need periodic inspection and replacement. The designers work closely with the aircraft operators, e.g., pilots, to ensure that the ergonomics of the operations center, i.e., the cockpit, are responsive to their needs. A prototype is built and it undergoes extensive flight testing and certification before mass production is started. Pilots are trained to fly the new planes using simulators as well as the aircraft, and service and maintenance crews are fully trained for their respective jobs long before the first plane carries paying passengers.

The manufacturer must assemble a team of subcontractors to supply parts or fabricate subassemblies. But final responsibility for the overall performance of the completed vehicle rests with the manufacturer who turns the vehicle over to the purchaser after acceptance tests are successfully completed. However, the manufacturer maintains a long term, life cycle relationship with the purchaser for technical and market reasons. Manufacturers serve as an information hub for their products by collecting and digesting operating experiences from their many clients and feeding back this information to all purchasers of the aircraft. A history is normally maintained by the manufacturers and operators in order to document the operation and condition of each plane. Traditional pilot's log sheets and maintenance records are now being supplemented with computerized data files collected while the plane is in flight, continuously documenting the performance of key systems. Some aircraft, e.g., B-757, now have fully computerized maintenance manuals. A maintenance engineer has instant access to diagrams, parts lists, and step by step test and repair procedures on a laptop computer linked to a CD-ROM drive. Computerized systems will play an ever increasing role in the airplane life cycle. The newest jetliner being designed by Boeing, the B-777, has been called the "paperless airplane" because for the first time in commercial aircraft design, the entire design process is computerized. Analysis studies, parts lists, communications, etc., are linked to CAD drawings and central data bases that are shared among all subcontractors and team members.

While airplanes within a single type, e.g., B-747, have strong similarities there are many differences as well, even though they are produced on the same production line. Within otherwise identical airframes, airline companies have some freedom with respect to seating configuration, and kitchen and lavatory layout. Manufacturers often offer physically different variants of the same aircraft to meet special needs, e.g., stretch versions with extra seats, extended range versions, cargo versions. Over an airplane's life cycle it may undergo significant changes in use and renovations--older passenger planes are converted first to charter use and later for use as cargo planes. As airplanes age, engines are refitted to improve fuel efficiency and reduce noise and avionics may also be upgraded.

Despite the real differences between airplanes and buildings, there are many similarities. In our efforts to better understand how the process of building design, construction, and operation can be improved, features and trends from other industrial sectors such as the aircraft industry may serve as useful models to explore. These industries are not to be blindly copied in their procedures but viewed as a source from which future useful models and approaches can be selectively extracted.

Building Life Cycle Perspective

A time-lapse movie of any single building over its entire life cycle would show great diversity in its details but it would almost always be possible to extract a common set of sequential events from the process, in much the same way that biological organisms have a well defined life cycle. In the absence of catastrophic events, e.g., war, natural disasters, the cycle has the following major elements:

Design: involving initiation of the development cycle, definition of design criteria, securing funding, development of a detailed plan for the building from conceptual stages through complete documentation of a buildable plan.

Construction: involving creation of a team to construct the building as detailed in the plan, securing the materials and components needed for the building, assembling all of the elements into a whole structure and operating system following the "plan."

Commissioning: involving fine tuning the operating structure so that it operates as designed, and in a way that provides the needs of the building occupants and functions.

Operation: involving the day-to-day and year-to-year operation of the whole and its component parts and systems, to serve the needs of its occupants, which are always in a state of flux.

Maintenance: involving routine and periodic actions that maintain, repair, replace and adjust components and systems so that they provide the required service and performance.

Renovation: involving design, construction, and commissioning to allow the building to change to meet evolving occupant needs.

Reuse: involving design, construction, and commissioning to allow the building to meet a new set of performance requirements, different from those for which it was originally intended. Over time this may have additional implications for operation and maintenance.

Demolition: the end of the life cycle at which time the building is removed to make way for a completely new structure which begins the cycle over.

In the time lapse movie this life cycle appears to be a continuous activity, but in the real world life cycle of most buildings it is normally a highly discontinuous set of actions and activities. There are many different actors at each phase in the process and there are significant disconnects between the actors at many of the stages. Valuable information about the building and its operation is often lost forever or must be reproduced at great cost and effort.

Information Flow in the Building Life Cycle

If one were to plot the various flows in and out of the building over time (e.g., dollars, energy, people) one would find a number of additional patterns with varying periodicity and with different degrees of predictability and randomness. The energy flows would have diurnal, weekly, and seasonal patterns with repeating components as well as randomness introduced by weather, for example. Some of the energy flow pattern is tied to decisions made in design and construction (e.g., orientation, double glazing) while the remainder is based on recent maintenance practice (e.g., clean heat exchange surfaces) and current operation (e.g., lights off, drapes pulled). While in principal it seems the information required to understand all of these patterns and thus predict overall energy usage would be accessible, experience tells us it is costly, time consuming, and difficult to create a model that accurately predicts overall energy performance.

In some cases the information exists but it is not in the right format to meet the new needs in the life cycle process. Information about the assumed or planned operation of the building HVAC system may have been laboriously gathered and analyzed in the design phase. However a different set of actors with the responsibility to operate the system may be required to develop the operational procedures, practices and operating software without benefit of the results or insights from those design studies. Even within a single phase of the development or life cycle, the differing perspectives and data needs of different actors may make successful integration difficult.

Communication between team members during a single phase of the life cycle is important as is communication of the building knowledge base through the life cycle. The building description is not a static description but rather one that is continuously in a state of change. To be of value, the description must therefore be continuously updated to reflect both material and procedural changes that occur over time.

The same element of information is not of equal value at any place in the design or life cycle. The design phase is the crucial phase that has the greatest impact (both positive and negative) on all subsequent elements of the life cycle. Within the design phase it is well accepted that decisions made in the programming and schematic phases early in the process have the greatest impact. While it is often technically possible to change or reverse a decision later in the process, the practical constraint is often cost and time. Changes that are requested late in the process are often costly and incur time delays that may result in additional costs.

Interestingly, while the potential impacts of decisions made in the design phase can have huge economic consequences later, the economic investment in the design phase is one of the smallest of the life cycle building costs. Design costs are typically a small percentage, e.g., 5%, of the construction cost. The annual costs of operations (utilities, cleaning, maintenance) gradually overtakes the construction costs on a life cycle basis. The occupancy cost, e.g., salaries, typically exceeds the construction cost in the first year and completely dominates the overall life cycle perspective on the total costs of doing business. To the extent that better design can produce a more satisfying, healthy and therefore productive work environment, an adequate investment in design is clearly a cost-effective strategy. Better design should also result in lower energy operating costs which will often quickly pay back the incremental investment. If better design can provide both productive environments and more energy efficient buildings, it becomes a clear economic winner in any life cycle accounting. In a small number of buildings there is anecdotal evidence that the productivity argument has been used successfully to invest more heavily in design and in construction features. Unfortunately, judging from more typical real world response, the productivity connection is unknown or unclear, and the energy efficiency savings are uncertain. The result is that there is no compelling economic incentive to invest additional resources in design. This is despite the fact that almost everyone has spent time in a building that is so uncomfortable that productivity clearly suffered. The cost of lost productivity is also readily apparent. When overheaded salaries can easily exceed $50/hour, only a few hours of lost productivity per year will equal the entire energy cost of the occupant's office space and a few additional hours will exceed other operating and maintenance costs.

More powerful and more appropriate tools have the potential to address and correct many of the problems noted above. We focus on the design phase and then discuss how better design tools might be propagated further into the life cycle. Design fees and time are not directly addressed by such solutions. The optimist will suggest that improved tools will allow designers to complete the required effort at less cost. The pessimist (or realist) will counter that given the open ended nature of the design process, expectations will always rise so that improvements in design "efficiency" will be offset by rising client expectations and perhaps by the designer's interest to explore additional options at greater depth than they would have tackled previously.

Computers in Architectural Offices Today

Beyond the practical limitations of time and money, what is the role of computer-based tools in better design? Current surveys show that over 80% of architectural firms use computers in their offices. The most common use is for traditional office operations--e.g., word processing, spreadsheets, specifications. About 60% of those offices with computers use CADD (computer-aided drafting and design) packages although far fewer than 60% of office staff are CADD-literate and it is likely that not all buildings in offices with CADD packages are developed on such packages. Furthermore, the Drafting element of CADD packages receive far more use than the Design elements. In fact most CADD software packages are not well suited for much of the "what-if" nature of design exploration. They are much better suited for the design development, documentation and production end of the process which eats up a proportionately larger fraction of the budget than the design-decision making phase. Computers today are best at tasks that require speed, accuracy, repetition, production, etc.--they have yet to be established as key tools that directly support the more creative and exploratory aspects of design.

The inherent nature of computer based tools today with their hardware and software limitations severely shape and constrain the very nature of the design process. This is captured in the old saying that when one's only tool is a hammer, every problem looks like a nail. At a minimum designers need a wide array of different types of hammers, and ideally they would have an even wider range of more versatile and powerful tools readily available.

Computer hardware and software have the potential to radically change the nature of the design process, as well as the management and operations of buildings. In the 1990s computers are completing a 20 year transition from expensive, centralized facilities requiring a trained priesthood to operate, to a low cost desktop (or portable) tool used by every employee. Historically the first waves of desktop computer based tools simply translated a hand calculation process or handbook design process onto the computer screen, presumably increasing speed and reducing computational errors. The interaction of designer with the computer was often dictated by the hardware limitations of the computer or the limited perspectives of software designers who viewed the computer as a faster hand calculator. Interfaces with the computer were often complex and non-intuitive, requiring a significant learning effort to become proficient with the tools. Within the building design professions, it is important to distinguish between those professionals who worked largely with quantitative data e.g., engineers, and others who are more visually oriented, e.g., architects. While these distinctions are overly simplistic they are still broadly representative of the professions today.

New Tools for Building Design

What would ideal new tools for the design of energy efficient buildings look like and how would they perform? While the focus of our interest is energy efficiency, this would be only one element of a larger array of capabilities that designers need to address the full range of design issues. Energy efficient solutions will be most cost effective when they are fully integrated within the context of total building design--therefore the energy capability must be embedded within such a context. Since energy is not at the top of most designers' priority lists, directly advertising the energy features of a new tool will not win many sales. There are potential partners, such as utilities whose DSM programs provide incentives based on simulation results, who might cooperate in the promotion of better energy tools. The use of performance-based compliance pathways for meeting new energy codes may also be an adequate incentive to push design teams in the direction of using new energy tools. In the long term, adoption and use of more powerful energy tools will be facilitated when the energy modules are embedded within a broader set of building design tools that are intrinsically of greater interest and value to most designers.

New tools would expand from the narrow focus of quantitative building performance evaluation tools to broader "information" tools that address both the qualitative and quantitative aspects of building design, in a format better suited to architectural practice. They will combine the predictive power of evaluation tools with the ability to help the designer better formulate the problem definition as well as to help find a solution.

An ideal building design tool should:

<u>Be interactive with the designer, accommodate different users and skill levels, and match the design process</u>. While existing design tools are structured with the expectation that the design process will adapt to them, a more appropriate tool adapts itself to the way in which a designer works. It should allow concurrent exploration of many issues and address the relationships between them. Design mixes explorations down well developed pathways with iterative and unexpected investigations. The process of design is not one of searching for the "correct" answer, but rather it involves the simultaneous consideration and evaluation of a host of ill-matched issues. Exploration and intuition are two key elements of the process that are ignored by existing design tools. Furthermore, the design problem is often fully articulated or understood only during an attempt to solve it. This lack of a rigid structured procedure in design indicates a need for flexibility in design tools.

The design process is almost always a collaborative activity involving members of a design team that has been assembled for the duration of the job by the client or lead team member. Efficient communications and interaction among team members is essential for a good solution is arguably even more important when the subject matter is energy, a topic that many team members may not know much about or care to be involved in most of the time. This situation changes suddenly when an energy efficiency solution encroaches on the domain of another team member. At that time a full airing of the problem among the relevant team members and a strategy to resolve the conflict can be facilitated by effective communications. Overnight express and fax have already changed the way that businesses operate. Electronic mail and document transfer, videoconferencing, collaborative software that allows multiple authors or creators to simultaneously work on the same problem are all available in some form and are likely to reshape office environments and potentially designer-energy consultant, or architect-engineer relationships in the years ahead.

<u>Present information in an appropriate format for architects</u>. Most designers are not research-oriented and, in fact, there are few effective means in place for accessing research information. Design knowledge is more typically derived from individual practical experience and from image-based reference sources like architectural journals or first-hand observation of buildings. New tools would emphasize images and graphics over text, relate design data to performance in actual buildings, provide qualitative as well as quantitative assessment, and provides "access" to real-life case study buildings without the time and cost of an actual visit. The newest generation of emerging tools will provide "access" to unbuilt "virtual environments."

New tools that provide realistic images of buildings require massive data storage for still images and tremendous computational power if the images are to rendered from a building description or if real time video is to be utilized. Videodisk technology linked to a desktop computer puts the capability of accessing either 100,000 still video color images or 60 minutes of full motion video in an affordable package today. CD-ROM provides digital storage of the equivalent of 800,000 pages of text on a small disc with a marginal production cost of under $2. Coupling CD-ROM disks to a computer with image compression/decompression capabilities allows 15 frame per second video to be packaged on low cost CD-ROMs. The technology in this field is driven by potential multibillion dollar markets in home entertainment and business. Rapid technical progress and falling prices are therefore sure to continue.

More powerful computational engines that allow realistic views of 3-D scenes to be calculated on the fly open the door to virtual reality environments. In such an environment the designer can explore a virtual building that exists only within the designer's imagination and the computer's memory. It is far cheaper to learn from mistakes in a virtual environment than to make the same mistakes in concrete and steel. Head mounted goggles with motion and position sensors shift the view seen by the user as her head position changes. As she moves about in a large virtual space, her position can be tracked and incorporated into the changing electronic environment. There is growing interest and activity in this area but not yet significant and cost effective software tools. Several PC walk through tools allow the user to move through a space as viewed in the computer screen with motion controlled by a mouse or data glove. Aerospace flight simulators provide a glimpse of what a high quality virtual environment might look and feel like, but their cost reflects their sophistication ($20 million+/-). They incorporate motion and sound as well as visual cues and have become essential elements of both civilian and military aircraft development and pilot training. The power of flight simulators is their ability to safely simulate not only routine operational environments but also others that occur only infrequently in real life or those that would be dangerous. Building simulators would be equally valuable both for design as well as operator training. In the design phase, walkthroughs could help assess views, ergonomics, circulation and lighting solutions. A more sophisticated simulator might allow a full range of comfort conditions to be simulated, including radiant and convective effects. As a training tool for plant operators, the building simulator would serve much the function that flight simulators serve today. Nuclear power plants and some large industrial facilities currently use facility and process simulators to train staff so there seems to be no fundamental reason why such facilities couldn't be used in the building professions in the near future.

Provide Efficient Access to Large Data Bases by Chunking and Linking the data. Building designers suffer from information overload. Tools that make gigabytes of data instantly available to a designer will not help solve real problems unless the data can be stored, retrieved and manipulated in a reasonable way. Data should be accessible in discrete chunks and in multiple layers of complexity. Data elements could be explored through built-in links and pathways or through random access, allowing a wide variety of users to access different kinds of information in different ways with equal ease. When information needs are well specified or understood, users could access information by direct data searches, e.g., find an example of a library in a data base that is located in a cooling dominated climate and uses less than 30K Btu/year for lighting and cooling. The same data base could be accessed in a browsing mode where the user flipped though the electronic pages of a case study "magazine" looking for ideas, inspiration and potential solutions to problems that may still be ill defined. Ideally such a capability would use intuitive approaches that most designers use today and thus require only a minimal learning curve.

How would one create such a rich, yet accessible, knowledge environment? Hypertext documents store information in nodes, with associated software linkages to any number of other nodes. Unlike a traditional hierarchical data base, this linked nodes network is particularly useful for the organization and manipulation of irregularly structured information. Adding images, graphics, voice, animation and video to linked words expands the concept of hypertext to hypermedia. Imagine the possibilities of exploring a hypermedia database of energy efficient buildings. A carefully collected set of building photographs, time lapse video clips, interviews with occupants, measured and simulated energy performance data, cost data, construction drawings and documentation, specifications, are available on a CD-ROM and/or optical videodisk. You start with a tour of the building, moving a mouse along a floor plan and watching a sequence of color images of the interior as you move through the space. You pause in one location to examine the lighting in more detail. Clicking the mouse on any location in the space shows the light levels under the current sunny tour conditions; an alternative sequence will show the space and associated lighting levels under nighttime or overcast sky conditions; in a daylighted space an optional time lapse image series shows the room from sunrise to sunset. A mouse click on the light fixture calls up data on cost and performance, as well as links to other projects in which the fixture was used. An energy icon provides access to calculated design data on expected energy consumption, which can be compared to data accessed through the utility meter icon which shows actual consumption over the past year. The discrepancy is large so you search for all buildings that used the same lighting energy consultant, comparing predicted and metered data for that set of buildings. Returning to the building under study, you explore lighting quality in the space by examining photographs of the as-built conditions. You can also call up additional stored images produced by a ray tracing program of design alternatives considered but not used. Clicking on the icon of the lighting designer gives a succinct verbal explanation for the selection that was made; another mouse click calls up the full 30 page consultants report on which the decision was based. When the smiling (satisfied) and frowning (dissatisfied) occupant icons in the same room are clicked, they speak two somewhat contradictory views of the lighting quality in the space, both of which can be contrasted with the lighting consultants views. The basic hardware and software to create such a scenario exists today and enhanced tools are being developed for emerging business and entertainment markets. Initial user reaction to prototypes of such systems have been positive. While the level of effort required to create and implement such a hypermedia data base is large, one can imagine several pathways for its development. Multimedia building case studies could be developed as part of design assistance services for use by utility demand side management programs. Commercially developed data bases could be supplemented with data bases created by each design office using its recent projects. The templates for such interactive data bases could be provided by others, leaving the design firm the task of loading the data base with project information. Conceptually, this is just an extension of what most firms do today, which is to accumulate and organize results of each office project for use in subsequent projects. Some information would be readily available but other critical data such as energy performance and post occupancy feedback is not normally gathered by design firms. Creation of these data bases would therefore stimulate an interest in exploring these important, but underutilized, data gathering activities.

Provide design guidance and expert advice. An ideal design tool is more than an electronic reference book or number-crunching computer program; it should contain expert consultant advice or guidance. Most current computer-based tools evaluate the performance of existing designs rather than assist in the more difficult process of generating new designs. Most design tools also assume a fully educated user who is looking for a specific answer to a well-defined question. A more useful tool, particularly in the early stages of design, accommodates the user who may not know all the parameters to the design problem. The on-line "expert consultant" helps a designer formulate the questions to ask and flags issues or trouble spots in the search for solutions. These electronic assistants could be developed with a variety of personalities that span the range of their human counterpart. The quiet, introverted consultant is silent unless his/her advice or involvement is requested. The outspoken consultant intervenes with recommendations continuously. In both cases the electronic consultant may be silently analyzing the current design--the difference is in their interaction with the designer.

Expert systems have been successfully developed for problems that are largely diagnostic in nature but they have yet to be used very successfully for design. Expert systems encode knowledge from a domain of expertise into a set of rule statements and then mimic human reasoning to make decisions based upon the rules. There is an extensive literature spanning the last 20 years documenting the disillusionment of those who have attempted to apply knowledge-based systems to the solution of robust design problems. Expert systems probably can play a useful role in smaller scale tasks in the design process if the design criteria can be identified and an evaluation system with respect to the criteria can be created. In this mode we see tremendous opportunities for "energy design advisors" to assist architects and engineers in a variety of tasks throughout the design process. These could include assistance in the development of appropriate performance criteria and targets, assistance in the performance evaluation of components and systems, assistance in determining compliance with building codes, assistance in selecting or qualifying for utility rebate programs, etc. Numerous public and private sector efforts are underway to explore the potential of expert systems for such tasks. An expert system approach that might succeed in addressing a more complex multicriterion problem such as building design is one in which the overall problem is broken into computational portions that are analyzed objectively by the computer-based expert and more subjective elements for which the designer must make the decisions.

Whole Building Simulation Tools

Despite the emphasis above on a new class of tools for design, there will continue to be a need for simulation engines that can accurately and efficiently analyze the performance of building designs. We are likely to see the continued development of a next generation of both public domain building energy analysis tools as well as proprietary tools. These tools are being continually updated to be able to model state of the art systems that are being designed and specified. As with other parts of the software industry, future tools are likely to utilize object oriented programming in which libraries of software modules or "objects" are developed as the basic building blocks of programs. Shared object libraries represent a vehicle for better collaboration in the future between tool developers.

Simulation engines will also increasingly be linked to, or integrated within, CADD drawing environments. Most simulation engines require a large body of geometric data that exist within the CADD database but it is difficult to efficiently extract that data in an efficient form from the current generation of "point-line" drawing systems which don't recognize the more object oriented structure of energy simulation engines. CADD programs have been developed in prototype form to extract geometric data and attributes automatically as a building is being designed, and send the data to a series of simulation modules for further analysis. The lack of standards and the origin of most CADD programs as 2-D point line drawing tools slows the inevitable move toward a more friendly whole building representation that can be shared between a variety of modeling tools.

As a short term need, the output from whole building simulation programs needs to be improved much in the same fashion as the output from lighting simulation programs has progressed from the days of dot matrix tabular printouts to virtual reality walk-through systems. One major difference with a building's thermal performance is that one can't easily "see" what a building's energy use looks like--not in the same sense as one can view the results of a luminaire selection. New ways of displaying a building's energy use will need to be developed and tested to determine if the intended function can be derived from the graphic by a typical designer, or building operator. The equivalent of a real time utility meter in the corner of the computer screen with target consumption noted might help the designer to quickly track progress toward energy goals. Energy use is intrinsically a dynamic process on an hourly, daily, and seasonal basis. Advanced animations could show energy use and comfort conditions in a building as the weather and occupancy cycle through the day. Displaying the temporal pattern of such data should not be a problem; developing tools to summarize and interpret the data will be more of a challenge.

How does one implement some of the suggestions outlined above, with the overlying reality that private market forces are inadequate to generate the investments required to attack such a problem head on? Engineers, energy consultants and some architects use a variety of hour-by-hour and simplified energy analysis tools today. Both privately developed and public domain tools are undergoing a transformation to improve their ease of use, to extend their intrinsic modeling capabilities, to link with third party software, and to improve their operation in a desktop PC hardware environment. Given the cost and limited markets for such tools in the short term, development will center around clients with well defined needs and markets, e.g.,utilities with design assistance programs, needs that are mandated, e.g., compliance tools for standards, or needs that are not directly coupled to market sales, e.g., research. Incremental development of such tools will be driven by user feedback so that over several years they should evolve into more powerful tools that meet short term needs, as well as allowing growth to meet emerging needs for design, analysis, commissioning, retrofit, and building operations. With the rapidly evolving hardware and software industry within which computer-based tools are developed, this incremental approach carries some risk that one will be locked into technology that is rapidly being outdated by market developments. However the installed base of systems and user expertise changes more slowly, giving developers a somewhat better chance of keeping pace with user market developments.

Building System Design and Operations Tools

We can gain additional insights into the practical difficulties of developing more effective tools by examining a subset of tools for HVAC system design in more detail. If HVAC simulation tools are so great why don't more designers use them? One of the reasons is due to their input/output complexity. Take the psychrometric chart, for example, most architects and engineers were trained to understand psychrometric properties by tediously tracing through a conditioning cycle on the psychrometric chart. Almost all HVAC designers have mental pictures of what an HVAC process looks like on the psychrometric chart. Some designers still manually trace-out peak heating and cooling condition lines for every system they design. Yet, how many simulation programs map a building's energy use onto a psychrometric graphic? Would such a graph be useful? What new insights could it provide over the traditional x-y scatter plot of energy use versus ambient temperature?

Likewise, most HVAC built-up units are assembled by the design engineer using manufacturer's charts and literature. Although this process is quite common throughout the industry it does not allow the design engineer to easily simulate and "view" the anticipated energy use before the system is built. Even when component-based simulations are done it usually requires complex input/output skills. Advances are being made in this field both in the area of proprietary software and in the development of a public domain icon-driven simulation program that would allow a designer to choose components from different manufacturers and simulate their use once the built-up unit has been assembled. Such systems will have the look and feel of icon-driven data acquisition front-ends that are now available from several manufacturers. Assembling a simulation becomes as easy as choosing sub-components from menu, aligning them visually on the screen, connecting them and turning the system on to watch it run through various environmental and occupancy conditions.

At the level of designing for thermal comfort in an individual space additional tools and display capabilities are needed. The prediction of the air flow in a room can be simulated with fluid dynamics models and the output presentation could also be enhanced by computer graphics. Visualizing the air flow in a room with specific manufacturer's product would be similar to the ability that lighting engineer's have to view the anticipated lighting distribution from a given lamp/fixture/room combination. With the rapid advances in desktop computer hardware and software it is not out of the question to expect computers to deliver such capabilities in the future. Such systems could simulate and display 3-D flow visualizations of the airflow from a specific supply diffuser and return vent to ensure adequate air movement and delivery throughout the space. If pollutant sources were added to such a model it could also predict air quality throughout the space. Merging such information with field data on performance and comfort would be a significant help to HVAC designers. Major engineering firms use computational fluid models today on mainframe computers or large workstations for special projects where air flow predictions are important to design solutions. But placing at least some of this capability on the desktop, integrating it with related design issues such as air quality, linking it to component selection, and providing a feedback loop to field data should ultimately result in systems with improved performance at lower cost.

Linking simulation tools used in design with commissioning and operations is another major need. This will require an integrated simulation/EMCS/operations common language. As building EMCSs obtain more processing power it will become possible for them to have onboard capabilities to run the original simulation program side-by-side with the real data that is coming from the building. This will allow for more accurate commissioning since the building's systems can be simulated through different conditions. It will also allow for advanced diagnosis because the expected response and/or energy use can be simulated side-by-side and compared to the real performance.

This capability will create greater institutional memory because the building operators will have ready access to the original design parameters, notes from the engineer, expected operation, etc., by using the same simulation program that was originally designed for the building. This same capability will allow operators to train in an off-line "what if" mode while the EMCS operates the building. Such training has been shown to be useful in keeping operators alert and on their toes to unusual conditions. It also allows them to be able to retake control of the "wheel" if needed.

Currently, most designers are not equipped to perform new building design and retrofit analysis. Many designers have little experience with operating real building systems and rarely get the kind of measured data that can help them "fine tune" their design skills. Likewise, very few HVAC designers have the statistical background, and/or software expertise, to effectively analyze the data when they are available. Most simulation programs are very difficult to calibrate. This is compounded by the fact that it is even more difficult to be assured that the data that one is using for calibration are accurate and/or measure what is being simulated.

Finally, the very same "knobs" that have made the simulation programs so flexible in their design simulation capabilities have made them almost impossible to manage when one is calibrating them to a real building. This last point is made worse by a lack of consensus by field practitioners--many of whom are unwilling to reveal the "secret of the knobs" that was used to get the simulation to mimic a building's energy use--sometimes because it is viewed as proprietary and a source of job security. Some calibrated simulations claim accuracy of +/-5% which seems hardly likely when instrumentation at the site cannot measure the basic hourly whole-building thermal and electric signals beyond the +/-10% level.

Accurate and meaningful modeling of heating/cooling system performance requires adequate weather data. Ready access to accurate and representative weather data that can be fed directly into a simulation program will become an issue as more and more designers use simulation to answer questions about existing building performance. Currently, this is a serious problem because of the relative paucity of available weather data for many building locations and the lack of accepted models to translate data from "nearby" sites, e.g., airport, to the specific location of the building. There are also a lack of agreement on how to convert weather data from parameters that are measured directly to those needed in simulation and operations models (e.g., which algorithm should one use to convert global horizontal solar to direct and diffuse?). Buildings may increasingly come equipped with their own weather stations which then adds additional problems related to maintenance and calibration, and the influence of the building itself and its functions (e.g., reflected sunlight, exhaust air) as a local climate moderator.