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Integrating Advanced Façades into High Performance Buildings

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Abstract

Glass is a remarkable material but its functionality is significantly enhanced when it is processed or altered to provide added intrinsic capabilities. The overall performance of glass elements in a building can be further enhanced when they are designed to be part of a complete façade system. Finally the façade system delivers the greatest performance to the building owner and occupants when it becomes an essential element of a fully integrated building design. This presentation examines the growing interest in incorporating advanced glazing elements into more comprehensive façade and building systems in a manner that increases comfort, productivity and amenity for occupants, reduces operating costs for building owners, and contributes to improving the health of the planet by reducing overall energy use and negative environmental impacts. We explore the role of glazing systems in dynamic and responsive façades that provide the following functionality:

- Enhanced sun protection and cooling load control while improving thermal comfort and providing most of the light needed with daylighting;
- Enhanced air quality and reduced cooling loads using natural ventilation schemes employing the façade as an active air control element;
- Reduced operating costs by minimizing lighting, cooling and heating energy use by optimizing the daylighting-thermal tradeoffs;
- Net positive contributions to the energy balance of the building using integrated photovoltaic systems;
- Improved indoor environments leading to enhanced occupant health, comfort and performance.

In addressing these issues façade system solutions must, of course, respect the constraints of latitude, location, solar orientation, acoustics, earthquake and fire safety, etc. Since climate and occupant needs are dynamic variables, in a high performance building the façade solution must have the capacity to respond and adapt to these variable exterior conditions and to changing occupant needs. This responsive performance capability can also offer solutions to building owners where reliable access to the electric grid is a challenge, in both less-developed countries and in industrialized countries where electric generating capacity has not kept pace with growth. We find that when properly designed and executed as part of a complete building solution, advanced façades can provide solutions to many of these challenges in building design today.

Introduction

Open an issue of virtually any architectural magazine today and you will likely find an article or news item on a daylighted, “green,” sustainable building that has recently been completed or has just been announced by its owner. The architectural sketch of the concept or the photos of the completed building often look compelling but there is typically little hard data that allows one to accurately assess the success of the design. Measured in terms of completed construction these buildings represent only a tiny fraction of existing stock. However, they have captured the attention of a much broader audience in the building community, and are likely to grow in importance. They could be the precursor to a new generation of radically different building designs that could either help improve the quality of buildings and reduce adverse environmental impacts, or they could ultimately be viewed as a transient trend or style that becomes an inconsequential architectural footnote.

The single most striking element common to most of these buildings is their highly glazed or all-glass façades. These new façade systems present a significant challenge to the design and manufacturing community. All-glass façades have been promoted in the past as an architectural statement. There have been tremendous advances in structural solutions that make these designs physically possible. What is most interesting about the current generation of such buildings is that they are being promoted as energy efficient, environmentally friendly solutions that enhance the quality of the indoor space for occupants. These solutions are built on the results of 20–30 years of real advances in improved glazing technology, better building design tools and more sophisticated building operations. But they often still fall short of what is needed to convincingly make these façades a cost effective, widespread solution throughout the world. We examine the major energy-related performance issues and discuss further advances that are needed in order to consistently and convincingly achieve the performance potentials that are now often claimed for these systems. While the focus is on advanced façades, this paper necessarily has limited scope. We focus on a specific subset of those architectural criteria related to occupant performance, comfort, view, daylight and energy use. Additional critical performance issues such as structure, acoustics, and security are not addressed here, although in any given building application they may be critically important performance factors. Finally, the paper takes a North American perspective based on experience and trends in the North American marketplace. This should generate some useful comparative discussion to the extent that technology and design practice varies around the world.

Although change in the building industry characteristically occurs at a very slow pace, the last 25 years have seen significant advances in the nature of glazing systems for buildings. Windows have always been a critical element in building design but it is innovation in glass properties and performance attributes that have made it possible for the architectural window to fulfill its role without adverse impact on occupants and owners. The window has always been an essential element of the building façade, providing a distinguishing appearance from the outside of the building, and helping to define the nature of space indoors, by providing natural light with its attendant variable quantity and quality over time and weather. From the owner's perspective, better windows keep the natural elements at bay, keep unwelcome visitors out, and help to reduce annual energy costs. From the occupant's perspective, daylight in the building enhances the quality of most indoor spaces, and the view and connection with the outdoors provides essential amenity for the 21st century office or factory worker.

Fenestration systems in buildings, ranging from single windows to complete glass façades, share some common performance requirements. These requirements are often in conflict with each other and they often change over short and long time frames. Windows provide view but must control glare. Windows admit daylight but must control solar transmittance and resultant cooling loads. Windows provide a degree of connection with the out of doors or psychological comfort but they must also maintain physical comfort in the face of temperature and solar extremes. Windows provide natural ventilation but admit undesired air leakage and can create drafts. Most glazings and windows themselves are intrinsically static but they must respond over a wide range of climate and use conditions. Perhaps the single constant that best defines the performance needs of a façade system is the ability to respond to change. It is no wonder that even though glazing options number in the hundreds or thousands, glazings alone rarely can provide the full degree of additional control needed and provided by the "glazing attachment" or "window covering" industry.

Dynamic Performance Perspectives

Façade systems must be dynamic and flexible to accommodate change in the exterior environment and in occupant needs and desires, all within the context of the overall building system. The traditional view of window performance is a static perspective on a single building component. Conventional engineering design assumed a worst-case perspective and analyzed performance under worst case conditions. The design challenge was then to provide adequate heating and cooling capability under those peak conditions. Only limited attention was paid to the manner in which glazing performance was dependent on other building systems.

Design today takes a more enlightened perspective. Not only is there tremendous climate variability, but occupant needs vary significantly within spaces. This variation arises from several sources: occupant preferences, differences in clothing and metabolic levels, the variability in the nature of visual tasks present in a given space, and the effects of changing office tasks and changing company business needs. A relatively sophisticated level of dynamic control is needed when the desired building impact should remain relatively constant but the external climate driver is highly variable. External daylight levels can vary by a factor of 10 in a matter of seconds as the sun moves behind a cloud, but interior levels should be maintained within a narrower dynamic range.

Given this high degree of internal and external dynamic change it is only logical that glazing systems must have the ability to respond intelligently to such change. The most rapidly changing conditions are those related to solar gain and daylight, and it is in the area of dynamic control of solar optical properties that much of the current interest is focused. Automated blinds and shades have never achieved the acceptance in the US that has been achieved in Europe and it is likely now that the emergence of smart glazings will ultimately fill this important technology niche. The initial interest is dynamic control of intensity of transmitted heat and light, which will reduce glare and moderate cooling loads. A second objective would be dynamic optical control of light distribution within a space to moderate interior changes as the daylight provided by sun and sky varies widely. The challenge today is to provide this degree of dynamic control ideally without costly or complex technology, and preferably without moving parts. In addition to the façade elements that provide the direct control of heat and light, a control system infrastructure for the façade and the complete building with associated sensors, actuators, communications protocols and software-based algorithms must be implemented, commissioned, and operated reliably over long periods of time.

Technology Trends and Issues

If one reviews the architectural and engineering literature on the subject of glass façades two different viewpoints are consistently expressed. The first is a strong positive reaction to the imagery and objectives of advanced façade systems. At the same time there is a concern about the costs and long-term performance of the systems and a clear lack of quantitative data on actual performance from the perspective of owner and occupant. The limited information that is available is often anecdotal and incomplete, and even when it is reliable it is difficult to understand whether it can be applied to other building solutions that may appear similar but in fact may differ tremendously in their design and operational details.

<u>Two Approaches to Façade Control: Size and Scale</u>

Windows in buildings have progressed over time from small portholes to meter-sized punched openings and finally to complete all-glass building skins with associated structural elements. Although the image of the perfectly clear, uninterrupted glazing is a common architectural icon it is impossible using currently available technology to provide adequate environmental control with a single layer of glazing. Even switching to a sealed double glass unit with coatings and gas fills will not consistently provide adequate environmental control. In search of new solutions, designers and product suppliers now seem to be moving in two conceptually different directions to provide the needed dynamic control.

1. The trend toward miniaturization.

If one looks at the cross section of a façade one can describe the cross section in terms of a characteristic dimension. For variants of single and multiple glazings this can best be viewed as a solution at the ***millimeter*** scale corresponding to the thickness of the layer. The biggest breakthrough in glazing technology over the last 25 years has been the development and widespread use of large area, low cost, multilayer thin film coatings. These solutions operate at a characteristic scale that is 1000 or more times smaller at the ***micron*** or ***sub-micron*** level. Thin film coatings have dramatically improved the range of performance capabilities for architectural glazings. Good quality multilayer coatings had been in widespread use in precision optics for years but their small size, low yield and high price kept the technology out of the realm of architectural application. In the 1970s both the development and further enhancement of large-area magnetron sputtering and later improvements in on-line pyrolytic deposition have revolutionized the glazing business. Significant advances in quality control, production speed and reproducibility of thin films coatings have dropped the cost of sophisticated multilayer coatings from $500/sq.m to under $5/sq.m. The primary objective of the initial coating development effort was the transparent, low-emissivity coating on glass and plastic for heat loss control. Later developments added spectrally selective coatings that admit daylight with an intensity almost equal to conventional glass but with only half the solar heat gain. Different types of reflective low transmittance coatings can reject even more sunlight and control glare although view and daylight may be substantially diminished.

One can expect further significant breakthroughs in glazing performance at the micron scale in the near future. The most important short-term development is the commercial development of a thin film switchable coating. These “smart glazings” can change solar and light transmittance dynamically to respond to changing occupant and building needs. After 15 years of laboratory development these coatings are now being scaled up in prototype form for use in buildings. Smart glazings can be divided into two major categories, 1) “passively activated” such as thermochromic (heat sensitive) or photochromic (light sensitive), and 2) “actively controlled”, such as electrochromic, which can be switched as needed with a small applied voltage. Each of these should ultimately find a market niche but the actively controllable electrochromic is likely to be the preferred choice. If the remaining durability and cost issues can be favorably resolved, smart glazings could be the preferred solution for most façade applications. Smart coatings will address several of the most pressing needs involving dynamic control of sunlight intensity but will not fully address the challenge of better daylight utilization. More efficient daylight use suggests the need to redirect daylight as distinct from absorbing or rejecting it.

Directional light control remains the primary optical challenge for glazings. The 100-year history of prismatic glazing and glass block suggests that this is an old challenge. Reflective and refractive optical elements, holographic glazings, diffractive microstructures, micromachines, etc., all represent potentially viable technical approaches to creating planar glazings that can redirect sunlight into spaces. The fundamental challenge has been how to create such coating structures for light control at a scale and cost consistent with commercial products. The world’s material scientists are hard at work developing a wide range of new materials and fabrication processes that may provide new solutions. The science of nanotechnology can operate at a scale 1000 times smaller than even the micron thick glass coatings. This is a world in which molecules or even atoms might be assembled, or would self assemble, to provide the microstructures needed to control light. Huge investments are being made in the basic science and fundamental technologies to create nanostructured coatings and devices for other business purposes and light redirecting glazing technologies will benefit in time from this new fundamental knowledge base.

These materials science breakthroughs may also advance the decades-long search for a photovoltaic (PV) technology that can be directly integrated into a building façade with cost, performance and durability that makes it suitable for use as a standard product. The concept of a building that produces its own electricity is a powerful statement about the relationship between human activities and impacts on the environment. The solar energy falling on the skin of most buildings is more than adequate to power the building. Building-integrated PV systems that generate electricity have long been viewed as a goal for future façades but the prototypes deployed to date are unlikely to find widespread application due to cost and other functional constraints. Furthermore economics will continue to drive many investment decisions and unless the building is designed from the start to be highly energy efficient it makes little sense to employ expensive power producing technology to satisfy loads that can be more cheaply reduced or eliminated with alternative designs and equipment selections. If façades with advanced glazings can greatly reduce cooling requirements and electric lighting use then the residual electric loads might be a good match to the electricity produced by the building skin.

2. The trend toward large-scale double envelope façades.

While we wait for the materials scientists to perfect their magic at ever smaller scales, façade design has moved in the opposite direction. The latest elaboration on this evolutionary path moves from the ***millimeter scale*** to the ***meter scale*** and adds a second distinct layer to the façade, often with significant increase in cost but with new performance capabilities. There are several new taxonomies of design options but one of the most common approaches to these advanced façades is the use of various double envelope designs. This introduces at least two primary glazed layers in the façade, often in conjunction with sun control systems (***e.g.***, shades, blinds, louvers), light redirection systems and ventilation systems. The characteristic "thickness" of such multilayer, multifunctional systems is on the order of 1 meter. The fundamental difference in this approach, as compared to the "materials science" approach, is the addition of air flow to the capabilities of the façade. In some designs the air flow is primarily a thermal mechanism to reject or capture heat. In other systems the air flow is part of a larger building ventilation system, providing outside air for ventilation purposes without mechanical fan systems. Other hybrid systems may utilize air flow over building mass for thermal storage or provide ventilation air with preheat in winter. Some of these designs operate largely passively with bouyancy and other thermal forces but increasingly, the solutions employ valves, vents, actuators and controls that improve responsiveness and performance. In almost all cases these come with the penalty of added complexity, maintenance and cost. If the building ventilation system can be simplified or portions eliminated there may be other offsetting cost savings.

A detailed discussion of the pros and cons of double façade systems is beyond the scope of this paper but they do directly address the issue of building systems integration that is discussed below. The most significant uncertainties surrounding these more complex façade systems should be amenable to resolution with more research and study. These issues include:

- ***Cost***—Most façade systems are unique although there are some parts and systems that are being reused. To the extent that such systems involve extensive engineering and product development the costs inevitably rise. Strategies to produce systems using a standardized kit of parts might help reduce costs as well. The absolute first cost of the double façade will always be more than a conventional system using today's technology. However, advanced façades may allow tradeoffs with other building systems, ***e.g.***, heating and cooling systems, thereby offsetting some of the added first costs. As with other emerging technologies, when benefits are not well proven, the safe design response is to include backup systems that ultimately may not be needed but are included to reduce risk.
- ***Design tools***—The ability of an architect or engineer to accurately predict performance of an advanced façade system is much better than in the past but there are significant limitations that impede widespread use of the systems. These solutions require extensive engineering analysis with state of the art tools such as computational fluid dynamics to evaluate air flow and ray-tracing to evaluate daylighting performance. Even when these are used today, time and cost constraints keep them from being used as extensively as needed to explore the full operating regime of the façade system. And these stand-alone tools have yet to be fully melded into an integrated tool which can reliably model control strategies and impacts of occupant actions. The design process itself must be changed to effectively create these systems, requiring more design team integration at the beginning of the process to ensure that all the key disciplines are coordinating effectively. Since the façade now has lighting, HVAC, structural, acoustic, interior design and life safety implications all the professionals involved with each of these disciplines must coordinate their work, starting early in the process.
- ***Commissioning and operations***—Buildings are occupied when completed and it is frequently up to the new occupants to figure out how to operate the building systems. In a building with an advanced façade with motorized shades, operable louvers to redirect daylight, vents for air flow, etc., it is highly unlikely that the building will perform as intended without an explicit effort to tune performance to match expectations. A rigorous

commissioning program is needed after construction is complete to ensure that the building meets design specifications. Additional tuning may be needed over time as the building ages and experiences new climate conditions. Furthermore, the occupants need to understand the intended building operation at an adequate level of detail so that they do not inadvertently subvert the design intent or operation. Systems need to be implemented so that performance over time is tracked, required maintenance is completed and unexpected failures are addressed in a timely manner.

Integrating Advanced Façades into High Performance Buildings

The issues discussed above point to the critical need for integration in all aspects of design, construction and operations. While the concept is easy to understand, the actual implementation may be more difficult. The integration challenge is also further complicated because we are addressing a complex building system that is dynamic and responsive to changing occupant needs, building owner needs and societal needs. We discuss the challenges of façade integration at four different levels:

1. Integrating different aspects of façade performance.

The façade must dynamically modulate climatic extremes but in doing so it must operate as an integrated element in the overall building system. This dynamic view of glazing performance lends itself to a perspective of glazing and façade systems as an integrated part of overall building performance. Buildings must be designed and operated as an integrated whole rather than as a loose collection of parts. This suggests that glass and fenestration system manufacturers might even consider partnering with structural system suppliers to create thermal storage systems, with HVAC systems suppliers to create systems that can effectively utilize natural ventilation strategies, and with lighting systems suppliers and furniture suppliers to provide daylighting solutions. Building control systems that manage the overall building operations (traditionally lighting and HVAC) should now also manage an active façade system that helps to modulate cooling loads and lighting energy needs. Each time there is a distinct source for new building systems and controls there is an added burden on the design team, the contractor and the building manager to ensure that the cross cutting integration is effectively implemented.

The façade is the first level of control in the mediation between the rapidly changing outdoor environment, the evolving needs of occupants and the economic interests of building owners. In simplistic terms the role of the glass façade is to protect the building occupants from undesired environmental impacts outside the building while allowing the occupants the illusion of being "outdoors." More specifically, the functional performance goals are:

- Enhanced sun protection and cooling load control while improving thermal comfort and providing most of the light needed with daylighting;
- Enhanced air quality and reduced cooling loads using natural ventilation schemes employing the façade as an active air control element;
- Reduced operating costs by minimizing lighting, cooling and heating energy use by optimizing the daylighting-thermal tradeoffs;
- Net positive contributions to the energy balance of the building using integrated photovoltaic systems;
- Improved indoor environments leading to enhanced occupant health, comfort and performance.

Integration at this level involves a series of performance tradeoffs which has led to new perceptions of overall performance. Over several decades the conceptual role of glazings and more broadly, building façades, has been shifting. As the energy crisis of the 1970s loomed glazings were viewed largely in a negative sense as "energy losers." In the past 20 years a clearer picture of performance tradeoffs and the availability of new technology has changed the role to that of "energy manager." With use of state of the art technologies and some of the speculative solutions described above, the role of façades is further shifting to that of "energy neutral" and will ultimately become an "energy supplier."

2. Integration between the building and its occupants.

Occupants in buildings often have little input into the design decisions made in their name but they are the ones who live with the successes and failures of the designers and the product suppliers. Design invariably targets various specifications of user needs but these needs often do not reflect the wide range of intrinsic human variability and the range of tasks to be performed. The lighting needs of a young worker with normal eyesight will be very different from the needs of an older worker with vision deficiencies. Similarly the lighting required to proofread poor quality, handwritten paper forms will be different from lighting needed to work at a computer terminal. However, the design of the perimeter space in an office building is done without knowing which person or which task will ultimately occupy the particular space. Fortunately most people are flexible, intelligent and adaptive, and they implement solutions that work. Future façade systems and the offices adjacent must provide the same level of adaptability and flexibility by intelligently responding to changing human needs. Provision of this capability will place new demands on the designer and the product and systems suppliers. Consider an occupant in an office with a venetian blind. Sensing, control logic, and operation of a blind system has historically been a single integrated set of events. Glare from the window triggers the occupant to set the task aside and adjust the cords or handles of the blind. The person provides the sensing of environmental conditions, the control logic that says the glare was excessive, the physical adjustment of the blind that changes the conditions, and the feedback that says the change is acceptable. The action of the single person is separate from that of co-workers (potentially a problem in a shared space) and is completely independent of the overall energy management needs of the building. An intelligent façade must perform all of these functions, and address the building integration needs noted in the following section. Furthermore, any automated system will preferably have some form of occupant overrides so there is a new set of issues associated with this human-machine interface.

3. Integration between the façade and the operation of the entire building.

In this paper we focus primarily on issues related to energy use, comfort and performance but there are other important building level integration issues such as security and life safety. The two largest annual energy loads in most American buildings are lighting and cooling, and both are directly impacted by the operation of the façade system. Furthermore, peak cooling loads and HVAC system sizing will be strongly influenced by the façade system. Mechanical engineers traditionally size systems to accommodate worst case conditions and the reliability of the façade controls must be appropriately factored into these calculations. Overheating due to solar heat gain is a real problem even in northern European climates with frequent overcast conditions but it is an absolutely critical problem in most American climates characterized by lower latitudes and frequent sunshine. Operation throughout the year will consist of a series of tradeoffs. For example, in summer the façade must control sunlight penetration to reduce cooling but admit adequate light to reduce electric lighting. From an energy balance perspective there will be an optimal relationship between minimizing cooling and minimizing lighting, while minimizing overall building electric loads. This will depend on fixed parameters, ***e.g.***, type of glazing, as well as dynamic parameters, ***e.g.***, characteristics of direct and diffuse radiation at a given time. It may also involve assessment of operating conditions hours in the future since solar gain in the morning may contribute to peak loads later in the afternoon. In winter the excess gain may be welcome to reduce heating loads but will be useful only if it can be admitted in a manner that does not contribute to thermal discomfort and glare. Each of these assessments and optimization actions must be repeated for spaces throughout the building on a recurring basis, demanding an extensive building controls infrastructure and automation system and emphasizing the need for underlying models that accurately predict overall building performance.

4. Integrating the building/façade and the utility infrastructure (energy, water, tele-communications, etc.) which supports it.

Energy is perhaps the most important and immediate of these. In the U.S., buildings account for about 35% of all energy use and over 65% of all electricity is used in buildings. For many years, at least in the industrialized countries, we assumed that reliable supply of electricity was assured. Several countries have ongoing changes involving restructuring of the electric utility industry. These efforts have been motivated in part by attempts to improve market mechanisms that are intended to reduce costs to users. In California the experiment has gone poorly resulting in rapidly rising prices and rolling blackouts. The final outcomes are not yet clear. However, in the short term these events have placed new emphasis on electric load management in buildings. This problem has two dimensions - 1) an interest in greatly increasing energy efficiency and implementing strategies that minimize building electric loads at all times, and - 2) the ability of the building to curtail or shed additional electric load when requested, ideally with little or no negative impact on occupants. Failure to manage loads on hot days when air conditioning peaks results in rolling blackouts where power is turned off to a section of the grid for hours at a time. As a short-term response there is a massive effort to lower immediate power use by turning off lights and resetting thermostats. In the longer term as the electricity markets evolve there is likely to be an economic premium placed on the ability to actively manage electric load throughout the day, a need that is well met by a dynamic façade system if properly linked to building automation systems. This premium could be quantified in terms of the deferred cost of electric supply. Cost of advanced façades has always been a major impediment to their widespread use. With a utility infrastructure that utilizes "real time pricing" signals, actual electricity costs as seen by the building owner may rise significantly for short periods of time when the demand on the grid is greatest and supply is inadequate. Under such conditions owners may pay 10-20 times the normal cost of electricity. Façades that can provide good indoor environmental conditions during critical operating hours without electricity use for lighting or cooling could provide very large financial benefits. Of course there are significant uncertainties in planning an investment in a façade that should perform for 40+ years and trying to second guess the electric supply situation even 2-3 years in the future. But the operational flexibility and insurance against cost escalation provided by such systems should have some market value. Furthermore, such systems that reduce electricity use also help reduce long term environmental impacts of carbon emissions and will be useful under conditions where natural disasters, ***e.g.***, earthquake or floods, disrupt access to reliable power supplies.

Overall Systems Integration Perspective

Each of these four integration perspectives can be discussed as a separate item. However, this distinction is an artificial separation of performance issues that are in fact linked and integrated with each other. As a consequence it is clear that the "sustainable building" with advanced façades must have a smart control system that cuts across all four levels of dynamic performance: façade systems, people, building and grid. In principle any such system could be specified today as a research project but practically, the cost of such hardware and software systems would make them unaffordable. Fortunately there is a huge investment being made in the development of lower cost sensors, internet-based communications protocols, low cost storage and data transfer, real time diagnostic systems, and intelligent controls, all of which will ultimately improve overall system performance, enhance work environments and lower operating costs. Despite optimism that the technical problems are solvable there remain interesting challenges to integrate the technology with people and people with the technology. With façade and building systems that are increasingly automated, how does one train the worker to interact with the systems effectively? How much flexibility can individual occupants have in terms of setting their preferred environmental conditions if they happen to be inconsistent with building wide energy use goals? Can a control system learn new occupant preferences by "observing" occupant behavior for a few days? Are there privacy issues associated with systems that are this intrusive in terms of learning occupant preferences, habits, etc.?

Some early results from these studies are illustrated in the figures below which show two views of an electrochromic smart glass façade in an office building in Oakland, California, USA. A versatile control system was implemented that can be operated to adjust the window transmission and interior lighting to meet requirements for glare, comfort, cooling energy, lighting energy and view although not all requirements can necessarily be simultaneously achieved. In Figure 1, under overcast conditions the window is in its clearest

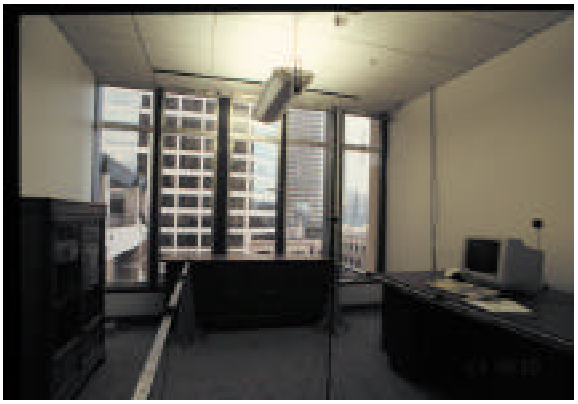

Figure 1. Overcast conditions.

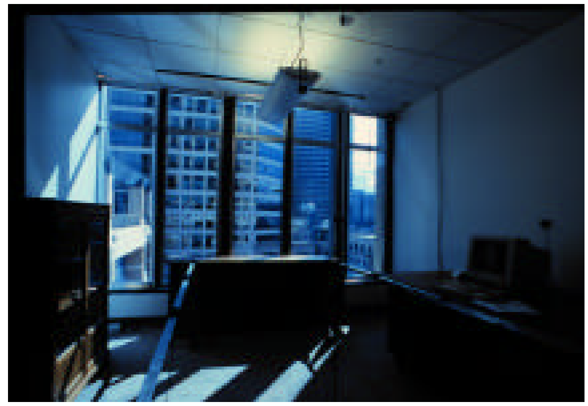

Figure 2. Sunny conditions.

transmission state but the lights remain on to meet the required task illuminance levels. Figure 2 shows that when the sun is present the window switches to its lowest transmission level to control glare and minimize cooling. In this state the task illuminance requirement is not met so the electric lights must provide some additional illumination. The upper row of small windows can be controlled independently of the larger view windows to separate the daylight admittance function from the glare control function. Further work is needed on control algorithms and optimization strategies to fully exploit the benefits of advanced façades. (For more information see Lee, ***et al***, Electrochromic Glazings for Commercial Buildings: Preliminary Results from a Full Scale Testbed, Lawrence Berkeley National Laoratory Report LBNL-45415).

Conclusions

Glazings and fenestration continue to be prominent elements of architectural form and expression. New technologies and better integration strategies provide the impetus to continue changing the perception of glass façades from "energy losers" to "energy managers" and ultimately to "energy suppliers." Many of the new sustainable buildings of the 21st century seem to have the use of virtually all glass façades as a consistent theme. While there is significant potential for these systems there is currently very little reliable performance data that characterizes their operation. We note two trends in evolving glazing and façade development—advances based on new materials science breakthroughs at the scale of microstructures, and simultaneous development and interest in large scale double envelope façades, where solar control, daylight redirection and ventilation air are all supplied by the new envelope systems. The emerging generation of advanced façades will increasingly incorporate dynamic elements to provide the control needed to accommodate changing occupant and owner needs and environmental conditions. Smart control systems will ultimately tie together integration strategies that support all aspects of complex façade function, and that address the interface between the occupant and building systems, between façades and building systems, and between façade performance and the operation of utility grids. The challenges that remain will consist of a mix of technology issues, process and economic issues, and the challenge of adapting the building occupant more comfortably in new roles in buildings with advanced façade systems.

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Further information resources:

A complete list of over 200 LBNL papers on the subject of glazings and fenestration can be found on our web site: http://windows.lbl.gov or can be obtained by contacting Pat Ross at (510) 486-6845 or via Email: PLRoss@lbl.gov.