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Advanced Interactive Facades –
Critical Elements for Future Green Buildings?

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1. INTRODUCTION

Building designers and owners have always been fascinated with the extensive use of glass in building envelopes. Today the highly glazed façade has almost become an iconic element for a “green building” that provides daylighting and a visual connection with the natural environment. Even before the current interest in green buildings there was no shortage of highly glazed building designs. But many of these buildings either rejected sunlight, and some associated daylight and view with highly reflective glazings or used highly transmissive glass and encountered serious internal comfort problems that could only be overcome with large HVAC systems, resulting in significant energy, cost and environmental penalties.

From the 1960’s to the 1990’s innovation in glazing made heat absorbing glass, reflective glass and double glazing commonplace, with an associated set of aesthetic features. In the last decade there has been a subtle shift from trying to optimize an ideal, static design solution using these glazings to making the façade responsive, interactive and even intelligent. More sophisticated design approaches and technologies have emerged using new high-performance glazing, improved shading and solar control systems, greater use of automated controls, and integration with other building systems. One relatively new architectural development is the double glass facade that offers a cavity that can provide improved acoustics, better solar control and enhanced ventilation.

Taken to its ultimate development, an interactive façade should respond intelligently and reliably to the changing outdoor conditions and internal performance needs. It should exploit available natural energies for lighting, heating and ventilation, should be able to provide large energy savings compared to conventional technologies, and at the same time maintain optimal indoor visual and thermal comfort conditions. As photovoltaic costs decrease in the future, these onsite power systems will be integrated within the glass skin and these facades will become local, non-polluting energy suppliers to the building. The potential for facilitating sustainable building operations in the future by exploiting these concepts is therefore great.

While the potentials are large, most are as yet undocumented and unrealized. The main R&D efforts in this sector are happening in Europe, where a number of recent high-profile buildings have demonstrated some of the technologies available today, notably in Germany, Netherlands, and UK. There has been less activity to date in North America although some noteworthy buildings have been constructed in the last few years.

Over the last 10 years LBNL has undertaken a research effort to explore the operation of interactive technologies for facades, focusing on daylight utilization, sun and glare control, and electric lighting controls with a prime motivation to reduce energy and electric demand. A focus on engineering and energy efficiency performance issues has been balanced with an occupant and owner perspective as well. The work explored the performance of special daylighting glazings, motorized blinds and electrochromic glazings. In 2001 in a broader effort to better understand how to facilitate development and adoption of these strategies and technologies, LBNL completed an initial assessment of high-performance commercial building facades in Europe and the US, documenting the current technology, tools and design practice (Lee et al. 2002). A key conclusion was that there is little hard performance data available to substantiate the commonly articulated claims about the merits of such facades. Beginning with a overview of the state of the art, the report outlines the critical R&D needs that must be addressed before such technologies can be routinely engineered to reliably deliver desired performance. These include sophisticated performance prediction tools, control algorithms for the complex interaction of different systems, design guidelines, post-occupancy studies of built cases etc. Other issues requiring further exploration are the comfort and productivity effects of these systems and the impacts of embodied energy use on life-cycle assessment of façade performance (Andresen et al. 2001).

Owners and designers indicated that the ability to reliably predict performance is a key prerequisite to further progress with advanced facades, as is the availability of cost effective hardware systems. Performance in this context includes the direct use of energy and associated electric demand and environmental impacts. But it should also include non-energy benefits associated with occupant comfort and satisfaction, and ideally productivity, as well as measures of indirect environmental impact such as embodied energy associated with the façade systems. Providing these answers will be a long and difficult challenge and LBNL has begun to address these needs by engaging an industry consortium in the US and collaborating with research partners overseas.

Interest in green buildings and sustainable design has often focused on the emissions and environmental impacts associated with life cycle assessment of materials used in the buildings. But the few studies available in this field suggest that the largest overall environmental impacts are those resulting from annual energy use associated with providing thermal and visual comfort in a building. The underlying energy and comfort performance issues are very well understood. A glass-enveloped building will normally be cold in the winter and warm in the summer, quite the opposite of our comfort preferences. The physical performance also leads directly to comfort impacts:

- Winter heat loss => energy for heating
  - ⇨ thermal comfort problems:
    - ⇨ low temperature radiation draught
    - ⇨ cold surface convention flow
    - ⇨ condensation, mold

- Summer solar gain => electricity for ventilation and cooling
  - ⇨ thermal comfort problems:
    - ⇨ direct radiation gain in occupied zones
    - ⇨ air temperature above comfort level

- Daylighting => glare from high luminance sky, reflected daylight
  - ⇨ glare from direct sunshine in occupied zones
  - ⇨ veiling reflections in computer screens

For a single building the energy impact is seen by the building owner ($10-20/sq.m.-yr) as one of many operational costs, whose magnitude is small compared to direct costs of ownership, e.g. maintenance, taxes, lease cost. But cumulative costs for the nation are large, as is the overall regional and global environmental impact of energy use. Glazing in commercial buildings today is directly responsible for about 1.3 Quads of annual energy use and indirectly influences another 1 Quad due to daylighting potentials. These energy impacts alone have an overall direct annual cost to building owners exceeding $15B/year with large associated greenhouse gas emissions. In the long-range view these impacts are unnecessary and unsustainable. The challenge is to reduce the thermal loads to the point where the winter solar gains and annual daylight benefits exceed the losses, thus erasing the current impacts and making the facades “energy neutral”. An ultimate objective is to properly account for the embodied energy in these calculations and to ultimately utilize energy generation in the skin to make these facades act as “net energy suppliers” to buildings, with appropriately low overall environmental loadings.

In this paper we review the recently completed work referenced above to better understand the nature of the challenges to achieving this goal, and discuss the nature of the collaborative effort and the work now underway to address the challenges, and the results to be expected as the work progresses.

2. THE INTERACTIVE FAÇADE

How can we convert a $15B/year energy problem into a sustainable design solution? The interactive façade will have to include systems that correct or moderate the performance of the glass as the outdoor conditions change, also allowing for individual occupant adjustment of the indoor comfort parameters. A static all-glass envelope will not be able to give optimal performance except for a few time periods during the year. Adding blinds that are irregularly controlled by occupants will not fundamentally change the performance picture. The conclusion is therefore that we need an intelligently controlled, dynamic envelope.

The current philosophy is to design the envelope with responsive, interactive systems, also often called “intelligent envelopes” (Wigginton et al. 2002). The envelope systems should react sensibly to the changes in the exterior climate and adjust solar gain, daylighting, heat loss, ventilation, and venting to the changing needs of the occupants and the building. In general, smart building controls and good occupant-level controls should be consistent and compatible but there are differences in philosophy and implementation. There is increasing evidence that occupants prefer strongly to have some level of personal control of their local indoor environment and that this might result in better overall work satisfaction and perhaps better performance and productivity. But there are potential conflicts as well - the occupant who prefers to have the blinds open on the west orientation to watch the afternoon sun may create problems for a building manager trying to minimize peak building cooling loads. Dynamic control is essential in all cases- the hierarchy of control priority is a matter for further exploration. Energy and comfort criteria are likely to be well correlated. Occupant preferences for temperature, light levels, view, etc are known to be consistent for a single individual but more variable between different individuals, thus providing some potential integration challenges.

The interactive façade concept is thus an effective starting point both to actively manage the changing “incident” climatic conditions and occupant interior needs based on both changing tasks and variable preferences. But the investment in new façade concepts also offers more direct exploitation of the natural energy flows offered by the external climate. This starts with better utilization of energy flows associated with daylighting and useful solar gain, but could be expanded by including wind and buoyancy driven natural ventilation, and building integrated photovoltaic systems, BIPV. The traditional role of the envelope as a filter is being replaced or supplemented with a more active role as an energy collector and transport system. Of course these new functions potentially add complexity and cost to the envelope, both in hardware and in “process” (both design and operations). These systems will ultimately only be widely used if their overall lifecycle benefits, measurable and perceived, exceed their costs and potential liabilities. That challenge defines the work ahead.

3. STATE-OF-THE-ART IN EUROPE AND U.S.

The all-glass building has for some time been a dominating part of new architecturally high-profile buildings in Europe, often designed by internationally-known architects. One important premise is that office workers have the legal right to daylight and view out at their workstations through building codes and health legislation in most European countries, contrary to the US situation. This often leads to extended floor plans with shallow perimeter zone depths, differing from practice in the U.S. which is characterized by more compact floor plates with less perimeter. Floor plans with extended perimeters often cost more than a compact design and may have greater thermal skin loads if the envelope is not suitably designed. The extended floor plan in Europe also permits greater use of natural ventilation via operable windows. In many European countries the ability to open a window is also considered a fundamental occupant amenity.

Recent research has shown that many occupants value the access to daylight and view, and the ability to locally control their environments. There is some evidence, largely anecdotal, that workers in spaces with daylight, view and control over their workplaces may demonstrate increased productivity. Even a very slight increase in overall productivity can provide large economic benefits and quickly pay for almost any indoor environment improvement, provided of course that this connection can be proven. This argument is now exploited by many architects in convincing their clients of the feasibility of all-glass buildings, despite the fact that there is little hard evidence to support it. But in Europe legal requirements and workplace expectations also reinforce these decisions, unlike in the U.S. Our informal surveys in the U.S. in 2001 indicated that owners were aware of, and interested in, the arguments in support of potential non-energy benefits of glazing and daylighting but in the absence of well documented data with a plausible causal link were skeptical and unwilling to make additional investments on this basis alone.

In the last decade European design of all-glass buildings has led to an interest in, and development of a double façade construction in order to be able to cope with the environmental problems associated with the highly-glazed facades. The construction encompasses two glass skins separated by a cavity ranging from approximately 15 – 150 cm. The double façade cavity serves several important functions. It provides a protected location for shading systems, and excess solar gain can be extracted from the cavity before it reaches the fully tempered areas and result in over-heating. In many buildings, the cavity is also integrated in a natural ventilation scheme, which may allow reduced investments in the ventilation system that can help pay for the more costly façade. Double facades may also enable window opening in high-rise buildings and reduce acoustic impacts of open windows with respect to street noise in urban areas. The systems have been used in small scale, low rise buildings as well as very large high rise construction. The glazing configurations and venting/ventilation schemes vary widely. From a design, construction, cost and commissioning perspective these façade systems present many new challenges.

The major European cities have already a large sample of such glass buildings in their commercial centers, most prominently in the UK, Germany, Switzerland and Netherlands, but also in other western European countries. The clients are often high-tech industries or financial institution, and the buildings are almost always presented officially as energy-conscious and “green”. Some research has been conducted through the R&D programs of the European Community, but the reality is that we do not really know in detail how they perform. Increased thermal and acoustical insulation, and opportunities for venting and natural ventilation are often listed as advantages for double facades. Increased fire risk and sound transmission via windows are noted as potential problem areas. The systems are costly as most are designed as one-of-a-kind systems although there is now a growing interest in standardizing some of the elements or systems. Judging from the pace of construction alone there is no lessening of the interest in these design solutions in Europe. In the U.S. we are now seeing the first “generation” of new double façade buildings reaching completion and occupancy, with more new ones underway. As in Europe it will be increasingly important to understand and document the performance these systems so that new designs are continuously improved.

Although double façade systems have captured the attention of many, our interest are more broadly on the topic of advanced interactive facades, which includes, but is not limited to, this subset of solutions. In section 4 our comments are addressed to a wide range of adaptive, intelligent envelope solutions.

4. PERFORMANCE ISSUES, TRENDS AND R&D DIRECTIONS

As with many trends and changes in architectural practice, the profession evolves slowly in planned and unplanned pathways, driven by a variety of business, technological, environmental, sociological and architectural factors. It is often difficult to understand the interplay of forces that shape progress with the advantage of hindsight- it is even more difficult to attempt to do this in "real time". However in reviewing trends in sustainable design and advanced facades in Europe and the US some early conclusions can be drawn and some issues appear to stand out as more significant than others. We summarize these issues, trends and R&D needs below in 6 categories and illustrate the points with experience from several recent projects. We mix together some trends that characterize market directions today with other future performance needs and objectives for R&D on advanced facades in the coming years.

4.1 Design of advanced facades will require better simulation and design tools, better ways of organizing the design team around the goals and better tools for commissioning and building operations

Traditional façade design is based on minimal use of simulation tools, primarily for peak load estimates. Dynamic, responsive systems must be analyzed under a range of diverse conditions for proper system sizing. The ability to create and model a "virtual building" and explore its operational modes with different glass façade controls is a major objective of new building energy simulation tool development such as EnergyPlus (http://gundog.lbl.gov). Tools that provide accurate optical and thermal properties of the façade elements, e.g. glazings, are available (http://windows.lbl.gov/software/default.htm) although more work is underway on the subject of optically complex glazings and shading systems. Advanced facades are now asked to provide additional control of ventilation air and daylight, requiring expanded use of tools that address CFD and daylighting performance for both energy studies and comfort assessment. Accurate modeling of performance is needed so that mechanical systems can be properly sized to meet loads. This requires a new degree of tool integration so that thermal and daylighting interactions of facades are properly considered as part of whole building energy modeling. In the future the modeling investment made for design might also be re-used for commissioning and operations (Lee et al. 2002).

Figure 1 Work in progress to develop automated interior shading control, glare control, and daylight dimming lighting controls for an all glass façade in New York City. The Radiance simulation program (radsite.lbl.gov) is used to simulate the dynamic performance of interior operable shading with fixed exterior sun control elements, for different orientations; results will be used to develop shade control strategies.

4.2 Advanced facades require greater first cost investment in hardware and façade technology, some of which may be offset by savings elsewhere in the building

In most cases the additional technology needed to provide new levels of dynamic control will add to the first cost compared to a base case building. In some cases portions of this increased first cost will be offset by other design changes, e.g. smart glazings could allow smaller chillers or elimination of conventional blinds or shades. Modeling studies suggest these values could lie in the range of \$30-\$150/m^2 but field data are sparse. These offsets involve more than detailed engineering calculations. Rightsizing a chiller system requires risk assessment on the part of the engineer that the operation of the building by the owner for years to come will follow original design intent. The U.S. General Services Administration is now building an office building in San Francisco without mechanical cooling on many of its floors, using cross ventilation at night from automated, operable windows. This was only possible with substantial additional design and analysis, and from a motivated and knowledgeable client who is able to link performance objectives in the design phase with commissioning and operational integrity after construction is complete (McConahey et al. 2002). There are also the traditional operating cost savings, e.g. energy savings, as well that will partially or fully amortize the added first cost over longer time periods. Future credits for demand response and time-variable pricing of electricity as well as carbon emissions could all add to the owners' annual benefits from buildings with advanced facades.

4.3 Advanced facades will require enhanced automation and better sensors and controls for optimal operations

Manual operation of windows or shades might work in home and some small buildings. In a larger building with many occupants and a design strategy that might involve predictive algorithms, thermal storage and/or integration of façade and lighting systems, ad hoc control by occupants must be replaced by more reliable automated controls. Such controls will accept inputs from a wide range of building sensors (wired and wireless) as well as anticipatory signals for predicted evening wind and temperature, day ahead utility price signals and next day expected building occupancy. New low cost sensors and controls with communications based on internet protocols have been developed and tested at our lab for motorized blinds and electrochromic windows (Rubinstein et al. 2000). Motors, actuators or dynamic coatings must activate reliably in response to control system outputs (Lee et al. 2003). Building automation systems will track and display key system performance metrics over time, providing comparison to archived performance data, and employ fault detection and automated diagnostics to correct faults when they are discovered. Our work also extends to exploring systems that provide building occupant feedback via the web to building operators.

Figure 2 Smart controls on the automated blind systems (left photo) keep direct sun out of the space, reducing glare and cooling loads. The same hardware system with different control strategies (right photo) admits sunlight to offset heating loads but creates excessive glare.

4.4 Innovation will improve hardware performance and reduce costs

Innovations over the last 20 years have reduced the overall U value of best-available glazing from about 3 W/m^2-C to about 1W/m^2-C with future potential to fall to .6. Spectrally-selective glazings transmit nearly all visible but reflect most of the near-infrared radiation in sunlight, thus reducing cooling loads. Delivering dynamic, responsive control of solar gain and glare, but permitting daylight use, is still the holy grail of façade technology. Improved motorized systems will be joined by the emerging generation of electrochromic smart glazings with coatings that dynamically change from clear to absorbing or reflective to reduce solar gain and control glare. R&D is focused now not only on development of better, cheaper coatings with improved durability and greater dynamic range but also on the systems integration issues that will allow maximum energy and non-energy benefits to be achieved (Lee et al. 2002). A new three-room field test facility at LBNL is now evaluating first generation systems solutions, directly measuring engineering performance data as well as occupant response. A longer term objective is “plug and play” technologies so that smart glass, dimmable lighting and other systems elements work seamlessly as a system without conflicts.

Figure 3 New LBNL facility for comparative field tests of advanced facades. Electrochromic glazings are controlled real-time to meet design illuminance but control solar gain and glare. Left: Under cloudy conditions the glass is at maximum transmittance. Center: When sun comes out the window begins to darken. Right: After 5 minutes the window is fully darkened but the lights are on to meet illuminance levels.

4.5 Field testing of design concepts and technologies plays a crucial role in understanding and validating system performance, and in building confidence in system performance.

Despite advances in modeling, measured field data will be required to convince many owners of the performance potentials. Field studies by LBNL over the last 8 years has provided limited data on automated blinds and electrochromics in test rooms in buildings in California with an emphasis on the integration of solar control, glare control and daylight dimming (Lee et al. 2000). New studies will continue this work at the LBNL test facility, and near New York City in an outdoor mock-up of a major new office building with an all glass façade, exterior fixed shading and interior automated blinds and dimmable lighting. These facilities not only provide engineering data and user response information but allow potential owners and design teams to experience the space firsthand, a critical step in adoption of new technology and design solutions.

Figure 4 Initial testing of electrochromic glazings in GSA office building in Oakland CA.; left: glazing is clear under dark overcast conditions; right: glazing in lowest transmittance state with direct sun (Lee, et al. 2003).

4.6 The performance of buildings and their infrastructure systems will be more intimately linked to the local or regional electric grid.

Sustainable design suggests that more attention be paid to the overall environmental impact of the building. Emissions from electrical energy generation are one of the largest environmental impacts of building operations. Although buildings may appear as standalone objects they are interdependent parts of local, regional and national electric grids, and the gas transmission infrastructure. Recent California experience with electricity shortages and more recently the northeast US experience with a massive power outage reminds us of the consequences of lack of reliable energy supply. More aggressive load management strategies may offer quicker and more cost effective alternatives to building more power plants. California is beginning to provide economic incentives for customers to adopt smarter building control strategies that are responsive to real time price signals from the electric grid. With proposed critical peak pricing programs in California, for 15 to 30 hours per year, with day-ahead notice, electric prices will rise ten-fold for several hours during hot summer days, with offsetting reductions during non- peak periods. Buildings with smart, responsive controls that can minimize electric use but maximize productivity and comfort can benefit from these new rates (Lee et al. 2002). The challenge for facades is to make the critical engineering tradeoffs between cooling and lighting use, while accommodating thermal comfort, glare and satisfaction of users. In these cases building owners might be given capabilities to effectively override the choices of individuals under critical demand response conditions. Responsive systems that are put in place for such price-responsive rates structures would also function well during emergencies caused by natural or man-made disasters or disruptions.

5. CONCLUSIONS

There is growing interest in highly glazed building facades, driven by a variety of architectural, aesthetic, business and environmental rationales. The environmental rationale appears plausible only if conventional glazing systems are replaced by a new generation of high performance, interactive, intelligent façade systems, that meet the comfort and performance needs of occupants while satisfying owner economic needs and broader societal environmental concerns. The challenge is that new technology, better systems integration using more capable design tools, and smarter building operation are all necessary to meet these goals. The opportunity is to create a new class of buildings that are both environmentally responsible at a regional or global level while providing the amenities and working environments that owners and occupants seek.

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