THE ROLE OF HIGH-COMPLEXITY LOW-RESOLUTION (HCLR) PERFORMANCE MODELING IN THE DEVELOPMENT OF DYNAMIC BUILDING ENVELOPES

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ABSTRACT

The present use of building simulation tools in the design of dynamic building envelopes provides critical feedback regarding the performance consequences of proposed design strategies. There is added importance on the use of low-resolution simulation engines during the early stages of the design process when most energy critical decisions are made by the design team. Even though low-resolution tools serve a critical role in assessing how well envelope design alternatives fulfill their intended level of performance, they are unable to predict precise outcomes. Therefore, these tools can complicate the design/construction process when incorrect assumptions about envelope performance are not revealed until late stages of the process. This gap between the predicted and actual performance of the system suggests that higher levels of accountability are required within the early design process to consider the complex aspects of dynamic building envelope behavior. This paper discusses the limitations of low-resolution tools in predicting dynamic building envelope daylighting behavior and presents a revised prediction strategy called High-Complexity Low-Resolution performance modeling employed at the Virginia Tech Center for Design Research. Utilizing a coupled approach, this method effectively interprets natural lighting data provided by low-resolution simulation programs and corroborates those results through operations such as physical modeling and rapid prototyping. When High-Complexity Low-Resolution performance modeling is used, the disparities between the predicted and actual daylighting results provided by the system is significantly reduced from 260 percent to 81 percent.

INTRODUCTION

Dynamic building envelopes are complex assemblies that serve a critical role in the context of full-building performance, orchestrating a wide array of performance factors such as the modulation of extreme climatic conditions, provisions for indoor environmental quality and the resourceful use of material. Instead of establishing a hermetically sealed boundary between inside and outside in service of a mechanically controlled steady-state interior environment, the operational characteristics of dynamic envelope systems offset the need for building energy consumption through integrated strategies including natural daylighting, cross ventilation and solar heating (Lang 2006). Considering the dynamic building envelope as a key factor toward

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achieving low-energy full-building performance necessitates a multifaceted workflow from design to realization. It is a process that demands the systematic evaluation of design alternatives due to the inextricable linkage that dynamic building envelopes inherently make between human, environmental and material factors across numerous timeframes. Without frameworks for systematic evaluation in place, decisions are made on the basis of assumption, using 'rules-of-thumb' approaches which fail to incorporate assessment routines that disclose the strengths and weaknesses of design alternatives relative to established performance criteria.

A critical step in the early design of dynamic building envelopes is the frequent evaluation of schematic options with the use of building simulation platforms. Building simulation is the process of testing a virtual replica of physical building systems relative to environmental factors such as solar radiation, air infiltration and thermal transfer in which observable output states are generated for analysis (Augenbroe 2003). These simulation engines offer a highly diverse toolset to the design team, facilitating evaluation sequences which acutely disclose how proposed alternative envelope configurations intensively shape the behavior of light, heat, and airflow present within the extensive environment. Within the spectrum of building simulation platforms, low-resolution tools are those that provide a highly interactive graphic user interface and are appropriate for use during the early design stages (Attia 2011). Due to the wide ranging analysis options provided by low-resolution tools, they are well suited for use by non-experts who seek to examine the various parameters that characterize a complex building envelope system. However, due to the propensity of low-resolution simulation engines to minimize prohibitively long computation times, they are configured to expedite calculations in favor of providing accurate or reliable results (Marsh and Khan 2011). This processing speed is often achieved by an overt limitation of building models with regard to material and system geometry, factoring out the components integral to any complex envelope system and thus limiting its ability to fully represent full envelope performance.

To account for the limitations incurred by low-resolution simulation tools, the Center for Design Research at Virginia Tech (VT-CDR) has developed a revised prediction strategy called High-Complexity Low-Resolution (HCLR) performance modeling. HCLR performance modeling, as referenced in this paper, is an alternative method of early envelope testing that examines the effective interpretation of feedback provided by low-resolution simulation programs and the corroboration of results through physical modeling and rapid prototyping. HCLR performance modeling uses a coupled approach whereby mathematical models and physical artifacts are used in tandem to assess the complex aspects of dynamic envelope performance. A summary of the opportunities that HCLR modeling provides include significant support for scalable operations, detailed performance analysis of system components and preservation of material integrity.

This paper presents dynamic building envelope research conducted by the VT-CDR where performance modeling tools are used in the design process to convey the multifunctional potential of envelope systems toward the conservation of energy. Two recent VT-CDR projects will be discussed which approach the use of building simulation in distinct ways. The first relies solely on the use of simulation to retroactively communicate design outcomes while the second employs a coupled approach which integrates building simulation and rapid prototyping operations within a shared experimental design cycle. The latter approach was adopted to effectively integrate simulation tools into the early design process instead of relegating these tools to the end of the process where they are used to merely communicate discrete quantifiable measures of system performance.

LUMENHAUS: OVERVIEW OF DYNAMIC ENVELOPE DESIGN WORKFLOW

To fully understand the value of HCLR performance modeling when integrated into the full scope of the design process, it is necessary to provide a brief overview of a dynamic envelope design workflow, which incorporates the use of building performance simulation tools. Over the past decade, the VT-CDR has constructed three net-zero energy houses and has participated in as many international exhibitions, which focus on the responsiveness of dynamic envelope strategies relative to the natural environment. This progression of research has resulted in the acquisition of considerable knowledge in the areas of sustainable design and energy efficiency in buildings. A workflow survey was conducted during this prolonged period to define the role of building simulation tools in the design of high performance building and envelope prototypes.

The initial project workflow surveyed was LumenHAUS (Figure 1), a net-zero energy house prototype developed by the VT-CDR for the 2009 Solar Decathlon Competition. Working from the concept of responsive architecture, the dwelling responds to external weather information and internal environmental conditions to minimize energy use and provide the highest quality architectural space. Over the past decade the building industry has witnessed an increasing interest in the capacity of physical enclosures to respond dynamically to changes in patterns of use and environment (Kolerevic 2013). The principal idea is that two-way relationships are established between dynamic enclosure systems and the environmental/social forces that pervade the built environment. Changes in either the natural environment or those initiated by the user group directly influence the configuration of the physical enclosure and vice versa. The result is an architecture that dynamically adjusts to change – an architecture that is adaptive, interactive, and responsive.

FIGURE 1. LumenHAUS Net-Zero Solar Decathlon Entry

Integral to the success of LumenHAUS is the *Eclipsis*™ dynamic envelope system (Figure 2). This mechanically actuated system regulates comfort as well as energy consumption within the building through variable control functions that enable response to ever-changing environmental and social factors such as solar radiation, prevailing airflow, or occupant use. The system is comprised of three primary layers; a perforated stainless steel solar shade, a translucent aerogel-filled polycarbonate panel, and a floor-to-ceiling sliding glass fenestration system. The stainless steel solar shade controls luminance and lighting density through rotated discs laser cut from18-gauge stainless steel sheet material. The size, polar rotation, and incidence angle of the disks are variable and set to parameters of solar exposure and visual privacy. System actuation receives input from one of two sources: a programmable weather station mounted on the house and an iPad interface operated by the user group. As the name of the project suggests, the design focuses on the advantages gained by sourcing building power, lighting and heating systems from direct solar exposure. Such a dynamic envelope system contributes to significant energy savings within the home by reducing demand for electric lighting through an ability to harvest direct solar radiation and provide ample natural interior illumination from sunrise to sunset.

FIGURE 2. *Eclipsis*™ Dynamic Building Envelope

The workflow survey indicated that even with access to building simulation tools, the VT-CDR team relied on older methods to develop the *Eclipsis*™ system during the early design phases. They relied heavily upon performance approximations which indicated daylight would penetrate up to 10-15 feet into the building, which was found to be suitable since LumenHAUS was 16 feet wide with a predominately glazed perimeter. Low-resolution daylighting simulations supported these assumptions indicating strong natural light levels throughout the interior. Once the performance benchmarks for daylighting were seemingly achieved, further study through testing and analysis methods was suspended. Therefore, building simulation tools were not used to iteratively test the efficacy of the proposed envelope system against the quality of the interior environment. Instead these tools were used to retroactively communicate the varying degrees of solar exposure and the amount of solar gain admitted through the stainless steel shade screen during the latter stages of the design process (Figure 3).

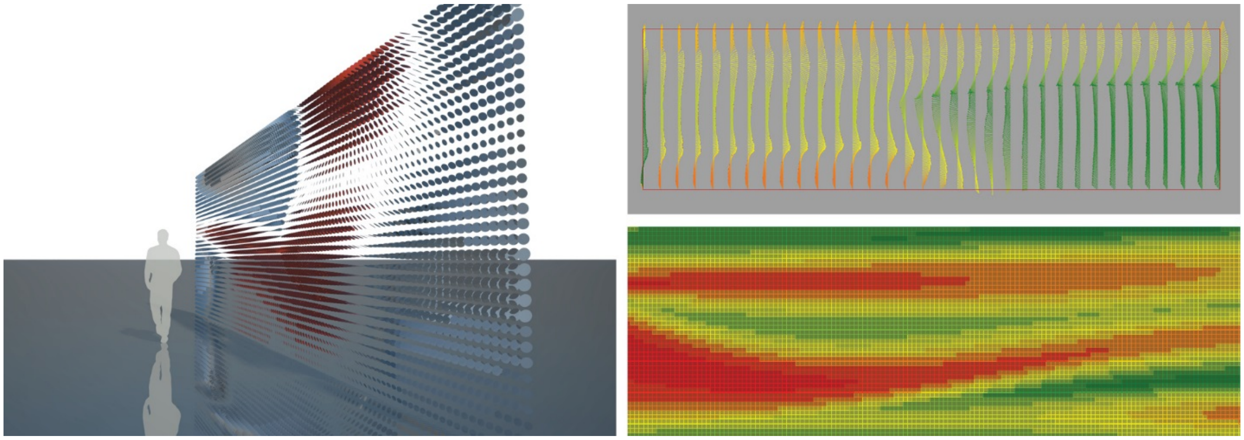

FIGURE 3. *Eclipsis*™ simulation analysis: a) left image shows solar exposure of shade screen disks and b) right images show solar gains on an analysis grid located on the interior side of the screen

This workflow sequence is not unique to the VT-CDR. With building certification and rating systems becoming more widely adopted and sought-after, sustainable design practices are encouraging the retroactive use of building simulation tools to virtually demonstrate design performance as a basis for point allocation. Green building certification programs such as the U.S. Green Building Council (USGBC) Leadership in Energy and Environmental Design (LEED 2009) rating system includes steps for the use of simulation software in performance modeling as long as the software meets the performance requirements set forth by ASHRAE 90.1. While these certification systems place emphasis on the importance of building simulation as an instrument for ex-post-facto analysis of design solutions; there is little consideration for the use of these tools in the early design stages where the most innovative performance decisions are made. While the LEED rating system continues to provide minimum performance metrics for daylight (minimum illuminance level of 250 lux on a clear equinox day in 75 percent of regularly occupied spaces) and view (direct line of sight for 90 percent of regularly occupied spaces), the reference guide only mentions glare control as a common failure for daylighting strategies. The use of shading devices to remedy this problem is recommended; however, there are no metrics provided to quantify the effectiveness of such control devices (Reinhart et. al. 2006)

Following the completion of LumenHAUS, on-site performance evaluations were conducted, including the systematic field measurement of lighting levels along a horizontal work plane located 32 inches above finished floor level to gauge the distribution of illuminance provided by the dynamic envelope system in its varying stages of operation. Measured in lux, the study defines illuminance as the amount of light power (lumens) falling on the unit area (square meters) on the horizontal test surface and is used to evaluate the adequacy of light for seeing objects indoors. Using a practice recommended by the Illuminating Engineering Society of North America (IESNA 2000), the house was measured using a portable photometer on a leveling platform along a grid of unobstructed test points with the electric lighting switched off.

The sky conditions were predominately unchanging during the measurement periods and could be categorized as clear sky to slightly hazy with minimal fluctuation in the natural light level.

The findings from these on-site observations and measures served to calibrate the numeric analysis from computer simulations set to similar parameters. The field measurement results indicated that the computer simulation engine over-predicted levels of illuminance within the building, representing on-average 180 percent of the lighting levels actually present within the structure. Moreover, many of the simulated to actual results at individual test points were also significantly different. These differences between actual and predicted results varied from 11 percent to 541 percent, demonstrating that low-resolution simulation tools are unable to adequately model the full scope of lighting behavior measured within the structure. Furthermore, the range of predicted results from 100 lux to 10,000 lux was much narrower than the range from 440 lux to 37,000 lux measured within the actual structure. This was largely attributed to the high degree of abstraction in sky condition necessary for the low-resolution simulation engine to compute daylighting levels (Figure 4).

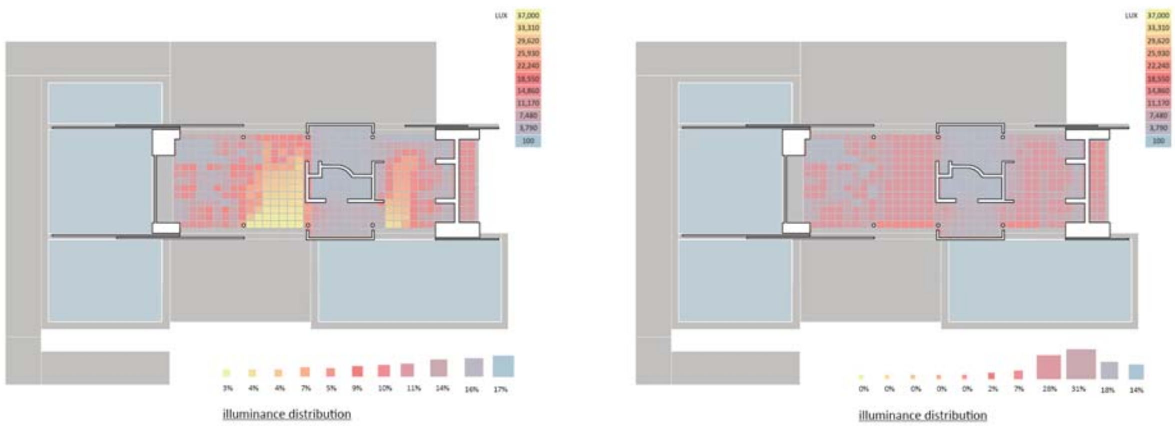

FIGURE 4. LumenHAUS illuminance levels: a) left image shows actual levels ranging between 440 - 37,000 lux and b) right image shows simulated levels ranging between 100 - 10,000 lux

These gaps between the projected and actual performance of the system suggests that higher levels of accountability are required if simulation tools are used within the early design process to adequately address the myriad factors associated with dynamic building envelope behavior. These gaps shed partial light on why simulation tools have not permeated the design practice after over two decades of market availability (Mahdavi et al. 2003). If modeling errors are unknown by simulation novices and inaccurate predictions are not identified by users lacking domain expertise then incorrect assumptions about envelope performance make their way into final building outcomes. The question for the evaluation of complex envelope systems then becomes: How can the design workflow foreground an acute understanding of complex system behavior using low-resolution toolsets configured to produce highly abstracted results?

The overall distribution of daylighting values between predicted and actual results suggests that low-resolution simulation tools are a suitable early assessment method when establishing the initial set of relative parameters for the dynamic envelope system. However, much can still be gained from using simulation as an early assessment technique by the design team prior to the engagement of expert contributors. These tools provide the ability to frame the most relevant questions during early design phases that directs the attention of specialized collaborators toward the most pressing issues to be resolved in a system's further development. This is where a revised approach can be effective, providing an acute understanding of how material and component assemblies contribute to the performance of a dynamic envelope system during the schematic stages of design.

HIGH-COMPLEXITY LOW-RESOLUTION MODELING METHODOLOGY

To pinpoint the deficiencies in the *Eclipsis*™ design workflow, a revised three-pronged approach was developed to reassess the performance of such an advanced daylighting system, namely the HCLR performance modeling process. This process is comprised of three main constituents: multi-state simulation, scaled physical modeling and full-scale component prototyping. The base platforms used to carry out the analysis used both computer simulation software and digital fabrication hardware. The computer simulation software used to explore the solar modulation of the *Eclipsis*™ system included Autodesk® Ecotect Analysis™ with the Desktop Radiance plug-in component. Autodesk® Ecotect Analysis™ is an environmental analysis tool developed by Andrew Marsh & Square One Research preferred for its user-friendly interface and ease of interactivity during the multi-state analysis stages. Desktop Radiance is a backward ray-tracing simulation software written by Greg Ward at Lawrence Berkeley Laboratories used to compute interior spectral radiance values in comprehensive daylighting analysis. The digital fabrication hardware used to study material and component parameters of the *Eclipsis*™ system included in-house CNC equipment in addition to those provided by the local manufacturing industry.

The initial stage in the HCLR performance modeling workflow involves multi-state simulation, exposing the dynamic envelope to external factors such as changing daylighting patterns culled from weather data sourced from the U.S. Department of Energy who regularly create and maintain weather profiles for multiple locations across the country. The ability to conduct multi-state simulations using the Ecotect Analysis platform enables the designer to circumscribe the envelope's performance, examining its response to multiple lighting factors. Conducting integrated daylighting, shading, and glare calculations on envelope attributes permits the designer to visualize how passive climatization and energy efficiency are achieved within the whole building. Additionally, Ecotect offers the ability to simulate various states within the same workspace providing the capability to look at a wide array of lighting characteristics. In the reassessment of the *Eclipsis*™ system, the range of daylighting illumination in the space could not be adequately addressed by the native daylighting analysis tool, therefore the functional network of the simulation platform was expanded to incorporate outside tools which were able to examine illuminance during key timeframes under variable sun angles and sky conditions. For example: the shading analysis tools inherent to Ecotect's base platform and the illuminance rendering engines provided by the Desktop Radiance plug-in were both able to identify areas of high lighting contrast in the analysis area. Contrasting light levels can be measured as the quotient of the lowest illuminance value on the test surface and the average illuminance on the same plane, whereby values below 0.4 are considered out of balance and can negatively impact light quality and occupant comfort. Shadow patterns highlighted areas of uneven lighting while the illuminance rendering engine quantified the level of contrast in those areas, identifying imbalance as severe as 0.09 leading to contrast glare and certain occupant discomfort (Figure 5).

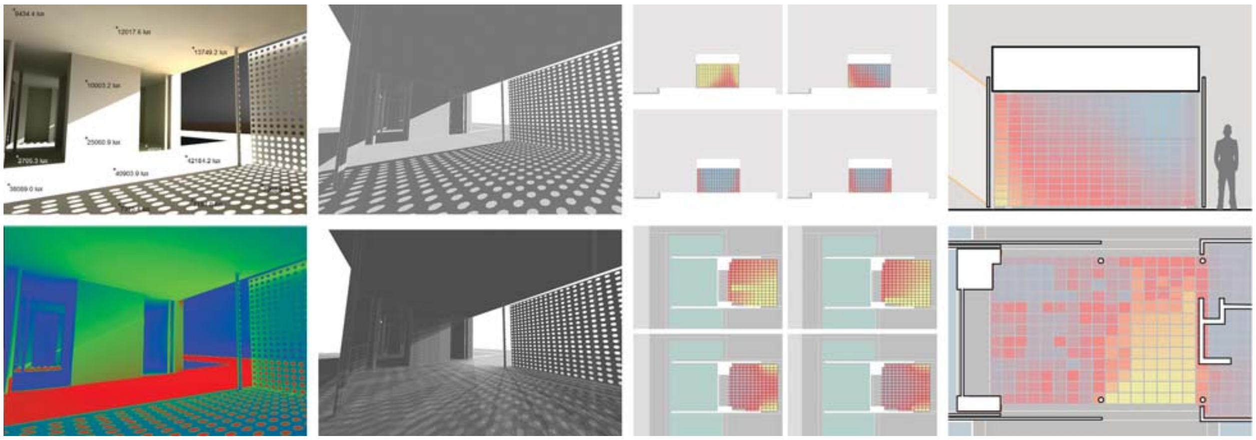

FIGURE 5. Multi-state lighting simulations of LumenHAUS: a) far left column shows illuminance rendering and color field analysis, b) left central column shows single and multi-state shadow pattern analysis, c) right central column shows illuminance values on horizontal and vertical analysis surfaces with varying sun angles and sky conditions and d) far right column shows illuminance readings on horizontal and vertical analysis surfaces in orthographic view.

The second stage in the HCLR performance modeling workflow involves the photometric testing of scaled physical study models. In this stage, three-dimensional material representations of the envelope system are constructed and located within small test cells where they are monitored against real sky conditions. These tests exploit the scalability of light, with a short wavelength of <1 millionth per meter, light behavior is accurately reproduced at smaller architectural scales and can be metered to determine the lighting levels present on interior surfaces of a test cell (Baker and Steemers 2002). Photographic surveys and photometric measurements of the scaled physical model are effective feedback tools because they place equal emphasis on light quality and quantity from human perspectives, assessing the degree to which the space improves occupant comfort and feeling of wellbeing (Osterhaus 1999). During the reassessment of the *Eclipsis*™ system, the physical model served a significant role in quantifying the non-uniform areas of illumination identified in the previous stage by building simulation programs. While the Desktop Radiance plug in component improves upon the native Ecotect daylighting engine by accounting for surface reflectivity, the physical study model improves upon these computer simulators in factoring the reflective material characteristics of interior surfaces. Unidentified by the low-resolution illuminance simulation tool alone, the scaled physical model disclosed a reflective glare problem produced by unwanted direct solar gain on interior surfaces generating illuminance levels as high as 15,000 lux, beyond triple the desired upper limit to maintain occupant comfort (Figure 6). Furthermore, the illuminance values in the scaled physical model were significantly closer to the values observed in the actual structure, predicting 81 percent of the lighting levels on average.

FIGURE 6. Test cell observations of *Eclipsis*™ system: a) left image shows photographic survey of scaled physical model, b) center image shows photometric readings in scaled physical model and c) right image shows reflected and direct solar gain observed in LumenHAUS

The third stage in the HCLR performance modeling workflow involves the photometric measurement of full-scale component prototypes. In this stage, small components of the envelope system are mocked up full scale and field measured to assess the behavior of the system at the level of the detail. Critical connections are prototyped using the proposed material palate to assess the role of system material in modulating solar gain. Predicting the intricate levels of directional light reflectance of advanced dynamic envelope systems like the laser-cut *Eclipsis*™ solar screen remain a challenge even for the most sophisticated building simulation tools (IENSA 2000). Therefore, full-scale component prototypes disclose the fine-grain nuances of envelope material which serves to compliment the abstract results provided by simulation engines. During the reassessment of the *Eclipsis*™ system, the illuminance values taken from the full-scale component prototype were significantly proximate to the values observed in the actual structure, predicting 130 percent of the lighting levels on average. Additionally, spot illuminance measurements of component prototypes identified a significant glare mitigation shortfall on the highly reflective stainless steel surfaces. Reflected glare is a major consideration in the design of daylight redirecting systems because of the intensity of direct sunlight. Therefore, incident reflection on system surfaces within the occupant's direct line of sight should be avoided in critical activity areas. When the full-scale prototype was photometrically measured, many of the rotated disk surfaces within the direct sightline of building occupants reached spot illuminance levels as high as 40,000 lux, causing discomfort for those engaging in activities within 5 feet of the system (Figure 7).

As discovered by the full experimental cycle of HCLR performance modeling, the over illumination of the interior could be spot metered using both scaled physical models and full-scale component prototypes to calibrate the output provided by low-resolution simulation programs. While the initial results of predictive modeling provided by low-resolution illuminance simulations disclosed daylighting levels in excess of the recommended upper limit of 4,500 lux, these tools alone were unable to reveal the severity of the problem. The HCLR modeling process was able to retroactively identify that maintained illuminance levels were actually as high as 15,000 lux, reflected glare levels within occupant sightlines were as high as 40,000 lux, and the non-uniformity of daylight was severe as 0.09.

FIGURE 7. Full-scale component prototype of *Eclipsis*™ system: a) left image shows component prototype being field measured in a test cell, b) center image shows reflected glare on stainless steel disks and c) right image shows view of *Eclipsis*™ from LumenHAUS interior

Following the survey of the Eclipsis™ workflow, some of the following deficiencies of conventional building simulation tools, as used in the original design phase were identified: 1) the approach was THRESHOLD CENTERED; once daylighting performance target values established by certification authorities were seemingly achieved, further investigations were suspended; 2) user ACCOUNTABILITY was lacking; initial simulation results were not corroborated against multiple criteria to recognize modeling errors and inaccurate predictions; 3) the design approach struggled to surmount the ABSTRACT nature of low-resolution simulation output, severely limiting the numerous factors which contribute to the complex behavior of an envelope system.

The HCLR approach addresses the inadequacies evident in the *Eclipsis*™ design workflow in three ways. First, HCLR performance modeling expands the role of low-resolution computer simulation in the schematic stages of the design process, using these tools heuristically to measure the fine-grain operation of the envelope within differentiated states. Procedures such as testing, experimentation, and revaluation are sustained by this approach due to the multitude of factors, scales, and timeframes that pervade the HCLR modeling domain. Second, HCLR performance modeling corroborates the results of these early simulations and in doing so increases the accountability for the design team member with limited domain knowledge. Using a coupled approach, multi-state simulation and physical prototype testing provide the opportunity to instill reciprocity protocols within the reiterative process. Using highly interoperable simulation and prototyping platforms enables the system to attune itself, whereby one domain branch can reinforce or critically examine the relative accuracy of another. Third, HCLR performance modeling supports concurrent multi-parameter decision making, examining the wide array of factors that play out across numerous scales during critical timeframes. This holistic approach adequately circumscribes the complex nature of any dynamic envelope system comprised of interconnected principles including aesthetics, environmental modulation, human perception, and material effectiveness.

URBAN GARDEN: CASE STUDIES AND FINDINGS

As Virginia Tech expands its research into the area of high-density housing, new dynamic envelope systems are being reconsidered to account for limitations of area and operability that stem from high-density applications. Ongoing design-build workshops at the VT-CDR explore the next generation *Eclipsis*™ system, suited for market in high-density applications. Like *Eclipsis*™ these second generation systems aim to diffuse direct solar radiation and naturally daylight interior space providing comfort for its inhabitants while continuing to reduce requirements for artificial lighting. However, these second generation prototypes accommodate operability within a fixed area while also increasing its range of operation in response to user and environmental input through a building control system (BCS) interface. To further examine the affordances provided by HCLR performance modeling, the VT-CDR is using this methodology to develop these next generation prototypes. Two prototypes will be presented which contain slightly different strategies toward adaptive enclosure and look to HCLR performance modeling to systematically identify the strengths and weaknesses of each scheme all within the purview of the early design process (Figure 8).

FIGURE 8. Next generation VT-CDR dynamic envelope prototypes: a) left images show ribbon scheme and b) right images show UV treated acrylic folding scheme

The first case study is comprised of vertically oriented thin perforated metal ribbons. Attached at both the base and the head of each panel, the system is designed to rotate independently about these points. Because of the high degree of reflectivity within the material, the challenge is to expoit the system's surfaces to redirect incident light while ensuring that these exposed surfaces are obscured from occupant view. The use of HCLR performance modeling is especially desirable in this case as it enables the VT-CDR to coordinate sun angle relative to the viewing position of the occupant, to assess the system's redirection of direct solar gain maintained viewing corridors through the system, and to examine the surface properties of the metal panel to redirect direct solar gain to adjacent interior surfaces. During the development of the design, multi-state simulation tools orient the ribbon geometry in relation to particular solar angles and tracks the polar position of the sun relative to the anticipated orientation of the system on the building. The system's range of movement can be parametrically tied to the animated angle of incidence as the sun moves across the sky. The materially accurate physical study model enables the VT-CDR to position cameras within the model to assess whether the incident gain on the surface of the stainless steel panels would be visible to the naked eye, causing intense areas of light that is unsuitable for direct view. While *Eclipsis*™ addressed this problem with the partnership of the insulated translucent panel, this strategy is considered inadequate in the Urban Garden application where the elevated view through the system was to be maintained during most stages of operation. Photographically surveying the physical model provides critical feedback toward maintaining view sheds through the system out to the surrounding context. Furthermore, the scaled physical study model provides the opportunity to assess the proposed interior surfaces and finishes, as the quality of the space is dependent upon the secondary reflective surfaces working in tandem with the primary light redirection system. Component prototyping measures the intensity of both incident and reflected light falling on surfaces that would be visible from the naked eye and those critical to the harvesting and redirection of light onto interior surfaces (Figure 9).

FIGURE 9. HDLR development of metal ribbon prototype: a) left images show multi-state simulation, b) center image shows photometric measurements of the scaled physical model and c) right image shows testing of the component prototype

The range of modeling inherent within the HCLR cycle is especially useful for the VT-CDR in examining the intensity of the light harvested by the highly reflective metal ribbons. The intensity of light on surfaces exposed to direct gain is metered in all three HCLR stages and are cross-checked against one another. During the evaluation process, the VT-CDR is able to identify significant improvements in the performance of this system compared to *Eclipsis*™. The new system demonstrates maintained illuminance levels within the desired range at 3,500 lux, worst-case reflective glare levels on system components at 7,000 lux within occupant sightlines, and uniformity of light distribution in the space measuring at .51.

The second case study is comprised of folded exterior-rated acrylic panels. Suspended from stainless steel cabling and custom hardware, the system is designed to fold into itself as it retracts into an overhead cavity. Because of the material's high degree of light admittance, the challenge is to configure surfaces to doubly transmit and redirect incident light striking system surfaces. The use of HCLR performance modeling is especially desirable in this case as it enables the VT-CDR to set the depths and angles of the multi-faceted system, to assess the uniform distribution of light on critical interior surfaces within the zones of greatest influence, and to examine the treatment of each acrylic panel to maximize the diffusion of solar radiation. During the development of the design, multi-state simulation tools set the cascading angles of the folding system in relation to dynamic characteristics of specific seasonal sun paths and sky conditions. Setting these angles to critical periods uses the envelope as a light shelf during hot seasons and a focusing lens to channel direct light to the non-visible interior surfaces where radiant gain provides heating potential during cold seasons. Scaled physical models enable the VT-CDR to visualize and meter the system's capacity to provide uniform level of daylighting on visible surfaces within the interior environment. While the Eclipsis™ system inadequately partnered highly reflective materials with intense luminance levels, the approach to the Urban Garden system aims to doubly provide views through the system while not sacrificing the system's ability to evenly illuminate the interior environment. Photographically documenting the physical model offers critical feedback about whether the system upholds these views and surveys the uniformity of lighting on interior surfaces. Component prototyping measures the reflection and diffusion of incident light transmitted through the system, enabling the VT-CDR to vary the treatment of the acrylic paneling for control over degrees of reflectance versus transmittance (Figure 10).

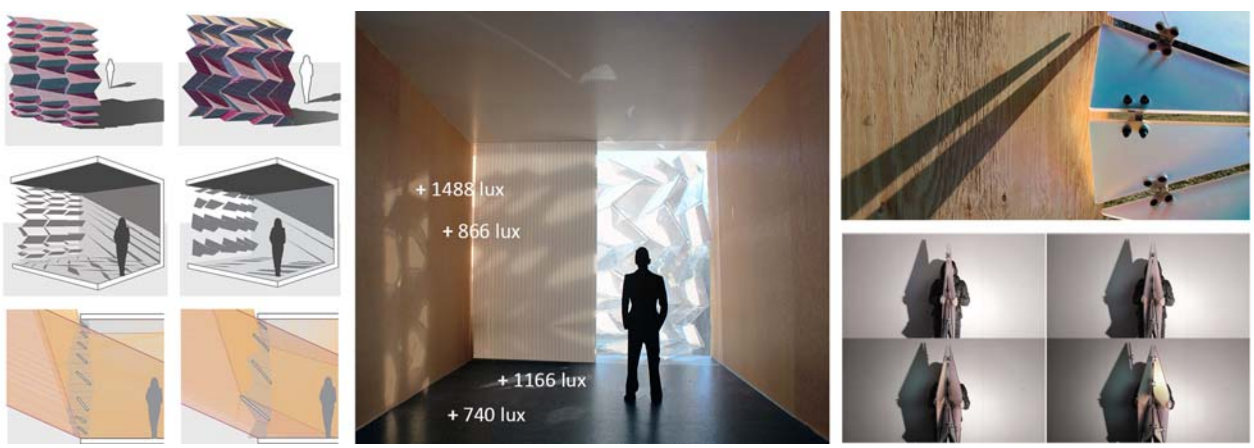

FIGURE 10. HDLR development of acrylic folding prototype: a) left images show multi-state simulation, b) center image shows photometric measurements of the scaled physical model and c) right images show testing of the component prototype

The VT-CDR finds noteworthy advantages to the coupled modeling approach provided by HCLR performance modeling, where the main goal of the project is to coordinate the material treatment of the acrylic panels with the uniformity of interior daylighting levels. Multi-state simulation analysis enables the team to track the relative distribution of daylighting values on interior surfaces, observe scaled physical models revealing the evenness of light distribution on interior surfaces from the human perspective, and develop component prototypes which disclose the quality of light transmitting through the acrylic panels. The even distribution of light on the interior is measured in all three HCLR stages and their results are corroborated against one another. Over the course of the early design assessment phase, the VT-CDR has identified significant light distribution improvements when using treated acrylic panels as a daylight re-directing system. This folded acrylic envelope demonstrates maintained illuminance levels of 1,200 lux that are central to the recommended range, reflective glare levels on system surfaces at 2,300 lux, and uniformity of light distribution in the space measuring 0.62 which significantly out-performs the other dynamic envelope systems presented.

Overall, the benefits of using the HCLR performance modeling methodology in evaluating the daylighting potential provided by the Urban Garden case studies are:

- Maintained Illuminance: calibrating the initial output from illuminance simulations with photometric measurements of both physical study models and component prototypes to examine how daylight sufficiency is provided by the articulated material enclosure
- Glare Control: using multi-state simulation analysis including shading projections and backward ray tracing analysis tools to corroborate direct observations of physical discomfort caused by excessive light present on material surfaces of scaled physical models and full-scale prototypes
- Daylight Uniformity: examining the distribution of illuminance values within zones of influence using illuminance simulations and photometric measurements of physical mock ups to identify areas where abrupt shifts in illuminance value cause user discomfort.

Dynamic envelope design sequences which aim to develop greater insight into the spatio-temporal complexities of daylight illumination require a holistic approach, focusing attention on how the material components of enclosure systems directly influence the behavior of the building’s lighting environment. The experimental cycle provided by the HCLR performance modeling platform reinforces this interconnected nature between the material enclosure and the ambient environment across critical scales and timeframes. This methodology tasks the material components of the envelope assembly to provide the most optimal lighting environment, offsetting the need for artificial lighting and subsequent energy consumption.

CONCLUSION

The use of HCLR performance modeling provides the opportunity to examine the complex nature of dynamic envelope systems early in the design process, increasing the reliability of results prior to the involvement of expert collaborators. The significance of processes like HCLR are being engrained at a crucial moment for the fields of building science, which are in the process of adopting the use of both low-resolution and advanced forms of building simulation in their workflows and exchanges. With emphasis upon performance-driven envelope design, the need for integrated testing between the material envelope and the resulting quality of interior environments requires effective modes for schematic design-development, HCLR performance modeling becomes a significant model for investigation. It is expected that with improved accuracy and geometry-based interfaces, more advanced forms of building simulation will enter into the schematic design fields. However, the need to test issues of perception, material, and fine-grain detail in dynamic envelope systems will always be of critical concern; and with the advancement of building simulation platforms, the further development of rapid prototyping and physical modeling equipment is just as inevitable. This research does not presume that the HCLR performance modeling platform will replace the advancing field of building simulation but will supplement these state-of-the-art tools as they gain trust and widespread adoption within the design field. The reciprocal workflow that arises from the HCLR platform situates results from building simulation programs appropriately relative to actual performance, in turn facilitating non-expert accountability through built-in reciprocity protocols and outcome corroboration. While this paper reports on the use of HCLR performance modeling in the area of dynamic envelopes as daylighting systems, much work is to be done to examine its application with regard to other passive climatization strategies such as natural ventilation and thermal gain.

REFERENCES

Attia, S. 2011. State of the Art of Existing Early Design Simulation Tools for Net Zero Energy Buildings: A Comparison of Ten Tools. Architecture et climat at Université catholique de Louvain. Louvain, Belgium.

Augenbroe, G. 2003. Trends in Building Simulation. Advanced Building Simulation. New York: Spon Press.

Baker, N. and Steemers, K. 2002. Daylight Modeling Techniques. Daylight Design of Buildings. London: James & James Ltd.

IESNA. 2000. "IESNA Lighting Handbook", 9th edition, Illuminating Engineering Society of North America, New York, NY.

Kolerevic, B. 2013. Building Dynamics: Exploring Architecture of Change. International symposium conducted at the University of Calgary. Calgary, Alberta.

Lang, W. 2006. Is It All "just" a Facade? The Functional, Energetic and Structural Aspects of the Building Skin. Building Skins. Basel: Birkhauser.

Marsh, A. and Khan, A. 2011. Simulation and the Future of Design Tools for Ecological Research. Architectural Design: Experimental Green Strategies: Redefining Ecology Design Research. Wiley, London.

Mahdavi, A., S. Feurer, A. Redlein e G. Suter. 2003. An inquiry into the building performance simulation tools usage by architects in Austria. Building Simulation. Eindhoven, Netherlands.

Osterhaus, W. 1999. Windowless environments: are they affecting our health. Proceedings of LIGHTING '99 - Annual Convention of the Illuminating Engineering Society of Australia and New Zealand.

Reinhart, C. Mardaljevic, J. Rogers, Z. 2006. Dynamic Daylight Performance Metrics for Sustainable Building Design. Leukos, Volume 3, Number 1.

US Green Building Council. 2009. LEED-NC (Leadership in Energy and Environmental Design). Version 3.0. from www.usgbc.org/LEED/.