Real-Time Multi-Zone Building Performance Impacts of Occupant Interaction with Dynamic Façade Systems

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Recent developments in responsive electroactive materials are increasing the rate at which next-generation façade technologies can respond to environmental conditions, building energy demands, and the actions of building occupants. Simulating the real-time performance of dynamic façade systems is critical for understanding the impacts that occupant response will have on whole-building energy performance and architectural design. This paper describes a method for real-time analysis of the multi-zone building performance impacts of occupant interaction with a dynamic façade system, the Electroactive Dynamic Display System (EDDS). The objective is to optimize EDDS implementation and define system limitations, incorporate EDDS as a dynamic factor in multi-zone building energy analyses, and provide real-time feedback of building performance data based on environmental conditions and occupant interactions. Preliminary results of parametric simulation methods demonstrate the ability of dynamic façade systems to consider real-time occupant interaction in the analysis of daylighting and thermal performance of buildings.

Keywords: Responsive façade systems, Occupant simulation, Whole-building analysis, Behavioral modeling, Real-time adaptation

INTRODUCTION
Many contemporary dynamic shading systems for building facades are driven by pre-set schedules set to optimize their dynamic movement for the reduction of heat gain and diffusion of glare. Building facades examples such as the New York Times Building and the Syracuse Center of Excellence each implement electronically controlled blinds that assume an optimized tilt based on solar geometry; however they do not necessarily allow a range of overrides to accommodate the comfort preferences of their individual office inhabitants (Krietemeyer and Godlewski, 2012). Maintaining some degree of variability is essential for both occupant comfort and for diurnal and seasonal modulation of solar energy. Motivated by studies demonstrating possible undesirable effects that automated environmentally-responsive systems have on occupant comfort, dynamic building envelope systems are being to embed greater aesthetic variability and manual user overrides into responsive behaviors, but not without recognizing the need to assess the potential risks and trade-offs associated with increased occupant control (Cole et al., 2012; Krietemeyer et al., 2015).
Advancements in responsive façades

Next-generation dynamic façade systems have the potential to respond to multiple stimuli with varying visual and thermal results. The recent transfer of electroactive materials to architectural applications is increasing the resolution and rate at which next-generation façade technologies can respond to fluctuating environmental conditions, building energy demands, and the unpredictable preferences and actions of building occupants. Examples of current design research in these areas include the Material Dynamics Lab, which experiments with electro-responsive smart materials for adaptive shading and daylight harvesting façades (Decker, 2013). Research at the Swiss Federal Institute of Technology is exploring organic kinetics in architectural applications to generate responsive architectural environments (Kretzer, 2013). The Sabin Design Lab at Cornell investigates the integration of passive materials, sensors, and imagers into responsive building skins (Sabin, 2015). The Rensselaer Polytechnic Institute’s (RPI) Center for Architecture Science and Ecology (CASE) is developing Electroactive Dynamic Display Systems (EDDS) for solar- and human-responsive building facades (Dyson et al., 2013). Heavily focused on the negotiation between bioclimatic and biological, or human-interactivity, the EDDS is designed to simultaneously minimize solar heat gain, promote the passage of usable daylight, mitigate glare, and offer a range of aesthetic visual effects, views, and privacy screens for its occupants. Current research on the EDDS is pushing for greater adaptability for solar control and user interaction by investigating micro to nanoscale implications through both physical material experiments (Thomas et al., 2015) and interactive computational simulations (Krietemeyer et al., 2015). Regardless of the specific material assemblies being developed across various research teams, the diverse approaches to the integration of new materials for high-performance façades are each focused on embedding multifunctional performance capabilities within these dynamic systems based on design criteria that includes architectural effects, environmental performance, and occupant control. Simulating the performance trade-offs of these new multifunctional systems at multiple architectural scales and according to various inputs is essential for supporting their prototype testing and integration within the built environment.

Methods for simulating dynamic systems

Simulating the real-time performance of dynamic façade systems such as the EDDS is critical for understanding the impacts that various degrees of occupant-response will have on multi-zone building energy performance and architectural design. Further, real-time simulations are essential for developing the parameters for designing the control systems for physical material prototypes as well as for understanding the limitations of the system when scaled up to building applications. However, current methods for real-time analysis of the relationship between complex dynamic systems-energy flows, building demands and occupant desires-within a single building model remain limited as commercial software tools do not yet provide a seamless feedback loop between these complex inputs at multiple scales of application.

Typical architectural modeling tools utilize a linear workflow whereby a single instance of a building is modeled in one 3d modeling program, such as Rhinoceros, SketchUp, or AutoCAD, with fixed parameters. The model is then exported and then analyzed in a separate analysis program, such as Ecotect, Vasari, or EnergyPlus (Lagios, et al., 2010). The linear and often disjointed workflow limits real-time information sharing between software. Further, the lack of a feedback loop of information can make for a tedious and time consuming process when testing the environmental and architectural effects of multiple states of dynamic systems, requiring the designer to manually manipulate the original geometries and parameters, export the model, and analyze the design repeatedly to test for building energy impacts.

The development of parametric simulation tools has begun to bridge the gap between design and
analysis workflow. Jakubiec and Reinhart outline a method for basic daylighting analysis and simulation that builds on the linear workflow of exporting a model to analysis software through the development of DIVA 2.0 (Jakubiec & Reinhart, 2011). This method is comprised of three main components: Inputs, model, and analysis. Inputs for traditional building analysis can be broken down into four areas: 1) The scene, which includes geometries, landscape, shading devices and material properties; 2) The area of interest, which is a user-defined area of a building to analyze, defined by sensor points and analysis grids; 3) Space usage which includes all of the set schedules for occupant, lighting, heating and cooling loads throughout the analysis period; 4) The climate data and time(s) of day to analyze. These four inputs are combined into one model that can then be exported to a simulation engine, such as DAYSIM, RADIANCE, EnergyPlus, Vasari, or Ecotect. Results may be numerical data sets, or a simulation visualization depending on the software used. While this parametric simulation workflow significantly enhances the design and analysis process in terms of time and variable results, it still faces challenges. It is mostly limited to basic predefined inputs and does not always accommodate analysis on a multi-zone or whole-building scale. Furthermore, it lacks real-time capabilities for analyzing the behaviors of complex dynamic systems. This is crucial for understanding how dynamic architectural systems negotiate their response according to fluctuating environmental flows and variable occupant preferences, which can often pose conflicts with regards to desires for views, privacy, daylight, and the need to mitigate solar heat gain.

EXPERIMENTAL METHODOLOGY
In addressing the challenges with the design and analysis workflow relative to the real-time, multi-zone building energy performance of occupant interaction with dynamic façade systems.
scalar analysis of dynamic facades systems and their response to environmental flows and variable occupant preferences, a simulation workflow is presented that utilizes a parametric base for analysis and simulation plugins within an easily manipulatable model. Using the EDDS as a dynamic façade system testbed, the objective is to provide a reiterative design and analysis feedback loop for analyzing the multi-zone building performance impacts of occupant interaction with dynamic façade systems. In order to achieve this, the workflow incorporates a series of fixed and dynamic inputs into a parametric model that is linked to a range of analysis and simulation tools (Figure 1).

Using the Rhinoceros algorithmic modeling tool Grasshopper, the parametric model is linked to analysis software through the use of multiple plugins, which constantly share data between the model and multiple analysis software. Not only does this circumvent the challenge of exporting a model to a separate program, but it allows for multiple analyses to be run within one script. For example, the workflow allows the designer to run a constantly updating DIVA daylighting analysis on any zone of a building while simultaneously taking into account the thermal energy loads of the entire building.

The parametric workflow supports the real-time simulation of complex dynamic systems on three levels. First, it simulates the dynamic response of the EDDS as it automatically adjusts to both the changing solar positions and the resulting daylight and thermal analysis of the interior. Second, it builds on the solar response feedback loop by simulating the dynamic response of the EDDS as it automatically adjusts to occupant proximity with the EDDS by either opening or closing for customizable views or privacy screens. The daylighting and thermal results of the combined solar- and occupant-response of the EDDS are analyzed within a single-zone model. Third, the daylighting and thermal results of the combined solar- and occupant-response of the EDDS are analyzed within a multi-zone model for the integration of solar- and occupant-response—a method that can also be applied to a whole-building energy model. By continuously feeding the analysis results produced by the simulation plugins as dynamic inputs back into the parametric model, a reiterative real-time feedback loop is achieved that simultaneously integrates occupant preferences for views and façade system response into a multiscalar daylighting and thermal analysis.

**Dynamic façade system parameters**
The EDDS presents an ideal dynamic façade system testbed for the methodology due to its ability to rapidly switch states to accommodate both fluctuating environmental conditions and occupant preferences for views or privacy. Comprised of multiple rolled metalized polymers adhered to the interior surfaces of an insulated glazing unit (IGU), each metalized polymer behaves like a miniature rolled shutter, individually controlled by an electric charge (Figure 2). When applied in an array to surfaces two and three of the IGU, double layers of individual shutters...
Two states of the EDDS with a viewing portal show the resulting sunlight penetration through a double-layered system in a fixed non-solar tracking position (left) and a double-layered system in the solar tracking state (right).

can each be programmed to roll up or down, thereby blocking or admitting direct incoming solar radiation for the mitigation of heat gain, daylight, and views (Dyson et al, 2013).

In modeling the dynamic façade system parameters in this workflow, a simplified EDDS material assembly is used with the objective to incorporate more detailed material spectral properties in future work. The properties of the EDDS are modeled parametrically using Grasshopper, and the EDDS shutters are defined as black 100% opaque surfaces that simulate the rolling and unrolling of shutters. Two layers of EDDS shutters, sized at 1 inch square with a .5 inch air gap, are used for the experimental simulations, and each shutter is its own entity that can respond to incoming data by rolling up or down. The degree of rolling of individual shutters is defined by dynamic inputs, such as the angle of the sun, the resulting daylight on the interior, or the proximity of a simulated person. When the EDDS shutters are dynamically responding to the altitude and azimuth angles of the sun, the shutters are programmed to position themselves in their solar tracking state, with dual layers of shutters staggered to intercept direct solar rays using minimal coverage. This allows the EDDS to block direct solar heat gain and glare while maintaining diffused daylight penetration and views through the open shutters (Figure 3).

**Occupant interaction parameters**

Within the presented workflow, occupant interaction with the EDDS can range from a single person or multiple people approaching an EDDS window to look out through a viewing portal, to create privacy screens, as well as to displaying media, advertisements and information. In modeling occupant interaction, the workflow accounts for the position and proximity of a single person or multiple people through the use of attractor points in Grasshopper, which act as dynamic inputs to the response of the EDDS. Each attractor point, or ‘person’, can trigger an infinite range of customized pixilated graphics or effects across the EDDS facade. For the purposes of simplified experimentation in this paper, occupant interaction is defined by a preference for a viewing portal in the shape of either a circle or square of various dimensions (Figure 4).

**Systematic compensation**

Another modification to the traditional building analysis method takes advantage of the real-time aspect of responding to various stimuli. Because Grasshopper allows for a constant transfer of data between the parametric model, analysis plugins and analysis
Occupant interaction with the EDDS can be defined by viewing portals of various shapes and dimensions that are triggered by the position and proximity of a single person or multiple people.

Software, the analysis results can inform how the dynamic system performs. This constant feedback loop of information allows for systematic compensation; that is to say that the dynamic facade system does not only respond to external stimuli, but it can also respond to the analyzed data produced by its own response to external stimuli. Systematic compensation solves the problem of occupant interference. For example, an occupant might interact with an EDDS facade by creating a personalized viewing portal, inadvertently allowing a rise in unwanted solar heat gain for that interior zone. The constantly updating building analysis provided in this workflow recognizes the deviation from an optimal performance value for heat gain and triggers the EDDS to compensate by adjusting its shutter densities elsewhere on the facade in order to meet the performance goals for heat gain (Figure 5).

**PRELIMINARY RESULTS**

The experimental simulations utilized a generic New York City office tower as a building model testbed. The 41-story rectangular office tower was situated at a 29-degree angle clockwise from true east-west (to match the Manhattan street grid), had a central core with a typical floor plate of 130 ft. by 180 ft., floor-to-ceiling double-glazed facades, and occupant and lighting schedules based on the standard office program. The simulations were divided into two categories: the single zone simulation which analyzed daylighting levels throughout an interior open space, and the multi-zonal energy simulation which analyzed the impacts of the façades on energy loads and temperature levels.

**Single-zone energy simulation**

The single-zone simulation analyzed the daylighting infiltration on a single-floor zone of the angled office tower facing both southeast and southwest (45 ft. wide by 25 ft. deep by 12 ft. high). Parameters for the single-zone daylighting infiltration simulation included clear sky conditions, material properties from an existing Radiance library (generic interior wall, generic floor, generic ceiling, double-pane low-E glazing), a high resolution semi-transparent EDDS facade (dual layers of ½ inch square shutters at 50% transparent 50% opaque non-responsive baseline), and four occupants with varying preferences for portal sizes to interact with the EDDS.

In a series of single-zone simulations, four separate glazing conditions were analyzed: 1) no EDDS (clear double-paned system); 2) non-responsive EDDS (double layered EDDS with no response); 3) EDDS with occupant response only (double layered EDDS with viewing portals); 4) EDDS with systematic compensation (double layered EDDS with occupant and environmental response). The first of four
simulations (condition 1) was a control test to determine the daylighting infiltration (%) without EDDS. Results from this DIVA-based analysis included values for daylighting autonomy, illuminance levels, and solar irradiation. In this case, the daylighting factor was a percentage result representing the amount of direct sunlight each point on the analysis grid (floor) received over the course of a year. For the single zone without EDDS, an average 7.49% of the space was flooded with daylight. After introducing a simple 50% transparent 50% opaque EDDS non-responsive baseline pattern (condition 2), average daylighting infiltration dropped down to 4.60%, blocking out excess direct sunlight which reduces glare and solar heat gains within the space. Occupant interaction was introduced to the analysis (condition 3), in this case with the use of viewing portals. Each occupant was 'tracked' throughout the space, and as he/she approached the 50/50 EDDS façade pattern, a portal opened up to allow for views out. This form of interaction unweltingly created a rift within the space, as the average daylighting infiltration increased, in the example shown, to 5.98%. To compensate, the script utilized the cyclical feedback loop of information from the previous analysis results. In this case the 4.60% baseline number from the non-responsive EDDS was set as a goal, and the EDDS façade surrounding the viewing portals compensated until the analysis results were closer to the baseline number (condition 4). In this case, the daylighting infiltration percentage of the single zone with EDDS responding to and compensating for occupant interaction was successfully reduced to 4.46% (Figure 6).

**Multi-zone energy simulation**

The multi-zone simulation analyzed the façade impacts on energy loads and temperature levels of eight stories of the same New York City office tower, including the entire floor plate with facades that were oriented southeast, southwest, northeast and northwest. While it is possible to analyze the whole-building impacts of the entire 41-story office tower through this simulation workflow, it requires more advanced computational processing power than what was used in the preliminary experiments. Therefore, an eight-story portion of the tower was used for the multi-zone simulation feedback loop with the same environmental, EDDS, and occupant inputs that were used in the single-zone simulations.

The same four glazing conditions were analyzed in a series of multi-zone simulations to determine the façade impacts on thermal energy requirements, indoor air temperature, mean radiant temperature, and zonal energy flux. First, the control test without EDDS (condition 1) gave expected results: the thermal energy requirements to cool the eight-story zone of the building were highest in the corner zone which faces the southeast and southwest, while the mean radiant temperature was also the highest in these zones. There was little variation in energy transfer (flux) between zones because there was not a drastic difference between how much sunlight penetrated each zone. The second analysis applied a baseline 50% opaque 50% transparent EDDS pattern to all of the zones (condition 2), which immediately reduced interior air temperature and mean radiant temperature by an average of 2°C and 3°C respectively. When four occupant interactions with EDDS were introduced to the model in the same manner as the single zone analysis (condition 3), viewing portals opened up across the building's façade, thus increasing the interior air temperature and mean radiant temperature. At this point, there was an increase in zonal energy flux variation due to the different daylighting infiltrations of each zone. Lastly, systematic compensation was employed to fill in the EDDS façade areas surrounding the viewing portals (condition 4) until the baseline goal was met. In this case, the goals for compensation matched the results from the non-responsive 50% opaque 50% transparent EDDS pattern. However, it was not necessary to set zonal energy flux as a goal in this case, as it will always be higher if certain zones contain viewing portals while other zones are compensating for these openings (Figure 7).
DISCUSSION
The experimental workflow presented in this paper provides significant opportunities for combining the design and analysis process to support the integration of next-generation dynamic façade systems that have the potential to respond and adapt to multiple stimuli. The simulation results suggest methods for optimizing EDDS implementation for a particular office program and according to a certain number of occupants, and it also begins to inform system limitations, such as the extent to which the EDDS can compensate when faced with conflicts between desires for large viewing portals and the need to reduce solar heat gain levels. The ability to support real-time analysis of complex façade building systems in the design phase reduces the risk of blind implementation that could lead to inefficiency or misconceptions about occupant control. It encourages investment into multifunctional building systems that promote participatory occupant engagement while offering a wide range of architectural design possibilities. The current workflow simulates occupant interaction using basic parameters for proximity and a limited number of interaction and portal types; however, the possibilities of generating a range of dynamic visual and informational effects using various sensing modalities based on simultaneous solar-and occupant-responsiveness makes this workflow a powerful tool for exploring the environmental, architectural, and social implications of any number of responsive architectural systems.

CONCLUSION
The experimental methodology demonstrated a real-time simulation feedback loop for single- and multi-
zone building performance analyses of basic occupant interactions with an emerging dynamic façade system, the Electroactive Dynamic Display System (EDDS). The parametric simulation workflow examined how highly responsive façade systems can reduce a building's energy consumption while simultaneously responding to occupant interactions, preferences, or overrides. Preliminary analysis results demonstrated that systemic compensation for occupant interaction with the EDDS had positive impacts on the single- and multi-zone daylighting and thermal performance of a building. While a single-zone and multi-zone analysis provided significant results with regards to the ability of a dynamic façade system to respond to both environmental and occupant demands, analyzing the whole-building impacts is a critical next step; however, with increased computational processing power, this simulation workflow makes it possible to analyze the whole-building energy impacts of solar- and occupant-responsive façade systems.

REFERENCES
Jakubiec, JA and Reinhart, C 2011 'DIVA 2.0: Integrating Daylight and Thermal Simulations Using Rhinoceros


