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Energy Modeling and Implementation of Complex Building Systems, Pt. 3

Kurt Rogler

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Energy Modeling
- and implementation of -
Complex Building Systems

Kurt Rogler
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Thesis Prep Fall 2014
Advisor: Bess Krietemeyer
Abstract

Complex/dynamic systems and technologies are gaining traction in architecture, but accurate analysis and simulation of conflicting dynamic systems within a building model has yet to be achieved. Most ideas of analysis and simulation revolve around a set process: model one instance of a building (i.e. without changing parameters) and analyze in a separate program. The use of a parametric base for analysis/simulation plugins, as well as an easily manipulatable and responsive model would not only further the accuracy of testing the effects of multiple dynamic systems, but become a new tool that merges model, behavior, analysis and simulation to strive for efficient implementation of these technologies and act as a platform for testing systems’ compensation for introduced variables (bio-responsiveness, enviro-responsiveness, manipulability, system-responsiveness). My method for testing this system utilizes Grasshopper, which excels at: providing a base for parametric plugins linking ‘static’ software, using data trees for complex behavioral modeling, and easing the manipulability of a parametric model. This method for analysis and optimization would facilitate the efficient implementation of dynamic/advanced/sustainable technologies in any number of building typologies.
Accurate digital modeling and analysis of complex systems in architecture (across four dimensions: 1. A dynamic system affecting architectural conditions. 2. Multiple dynamic + static systems affecting architectural conditions. 3. The behavior of each system as it affects, and the resulting behavior of, architectural conditions. 4. The behavior of the dynamic systems as they respond to said architectural conditions) is, at the moment, mostly unachievable.

Simulation of complex systems and their performance holds merit within the design phase for many reasons:

Attributes of complex systems occur on a case-by-case basis. It is difficult to speculate the performance of a system before implementing it unless there is reference of a similar building type utilizing the same technology in the same way in an equivalent climate zone.

Taking this into account, an accurate simulation engine analyzing complex systems will foster more implementation: If a developer can see the system in action, he/she may be more likely to invest.

There are standards set for sustainable building design which require the analysis of complex systems pre-construction. LEED standards dictate:

A whole-building energy simulation to find the minimum energy performance required & a simulation of spatial daylighting autonomy and annual sunlight exposure.

Issue of Interest

Accurate digital modeling and analysis of complex systems in architecture (across four dimensions: 1. A dynamic system affecting architectural conditions. 2. Multiple dynamic + static systems affecting architectural conditions. 3. The behavior of each system as it affects, and the resulting behavior of, architectural conditions. 4. The behavior of the dynamic systems as they respond to said architectural conditions) is, at the moment, mostly unachievable.

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A whole-building energy simulation to find the minimum energy performance required & a simulation of spatial daylighting autonomy and annual sunlight exposure.
Other Dynamic Systems Examples

Current question on dynamic systems:
1. How do we simulate the impact of these systems pre-construction?
2. How do we simulate these systems’ reactions to results from [1]?
3. How do we analyze data from simulation [2] to impact the use of the system?

Electroactive Dynamic Display Systems (EDDS)

With the potential to be bioresponsive, enviroresponsive, manually operated, dynamic or static, EDDS can be generalized to a manipulatable/controlled facade of ‘pixels’ which can be turned transparent or opaque. On a building scale, this would affect interior air quality/temperature, and daylighting levels, and the system has potential as interior partitions, providing an atmospheric effect.

The Living: Breathing Facade

Flexible wall that ‘breathes’ according to shifting conditions outside. It could also be used as a system for interior airflow control. It is enviroresponsive.

Kiefer Technic Showroom & Al Bahr Towers

Both buildings utilize manipulative facades which can emulate a design strategy or simply be a performative aspect for the building.
Current Strategies

Daylighting/thermal/air quality/etc analysis and simulation software tools currently exist to accurately map out any number of pre-construction conditions. Two main software examples include EnergyPlus and OpenStudio, both developed/funded by the US Department of Energy, which import .idf digital models with .epw weather models for site to accurately analyze specified zones of a building. Within these programs are thousands of preset implementable building standards, from programmatic-based usage schedules, to HVAC systems.

Typical methods of achieving whole [or partial] building simulations rely on completed digital models which are exported to the aforementioned software tools for analysis. The resulting simulation only provides faults, and not recommendations for improvements.

More recent attempts, such as those by Christoph Reinhart, combat this model-then-analyze ideology. Plugins developed for 3D modeling programs facilitate the link between model and analysis/results in a way that allows the designer to keep manipulating parameters on the model until a desired analysis result is achieved.
EnergyPlus

EnergyPlus is a whole building energy simulation program that engineers, architects, and researchers use to model energy and water use in buildings. Modeling the performance of a building with EnergyPlus enables building professionals to optimize the building design to use less energy and water.

EnergyPlus models heating, cooling, lighting, ventilation, other energy flows, and water use. EnergyPlus includes many innovative simulation capabilities: time-steps less than an hour, modular systems and plant integrated with heat balance-based zone simulation, multizone air flow, thermal comfort, water use, natural ventilation, and photovoltaic systems.

- energy.gov

OpenStudio

OpenStudio is a cross-platform collection of software tools to support whole building energy modeling using EnergyPlus and advanced daylight analysis using Radiance.

-openstudio.nrel.gov

Radiance

Radiance is a suite of programs for the analysis and visualization of lighting in design. There are no limitations on the geometry or the materials that may be simulated. Radiance is used by architects and engineers to predict illumination, visual quality and appearance of innovative design spaces, and by researchers to evaluate new lighting and daylighting technologies.

-radsite.lbl.gov/radiance/

DaySim

DAYSIM is a Radiance-based daylighting analysis software that models the annual amount of daylight in and around buildings. DAYSIM allows users to model dynamic facades systems ranging from standard venetian blinds to state-of-the-art light redirecting elements, switchable glazings and combinations thereof. Users may further specify complex electric lighting systems and controls including manual light switches, occupancy sensors and photocell controlled dimming.

daysim.ning.com

EvalGlare

A Radiance-based tool to evaluate daylight glare in office spaces.
Grasshopper Plugins:

Ladybug

Ladybug is an open source environmental plugin for Grasshopper3D that helps architects and engineers create an environmentally-conscious architectural design. Ladybug imports standard EnergyPlus Weather files (.EPW) into Grasshopper and provides a variety of 3D interactive graphics to support the decision-making process during the initial stages of design.

ArchSim Energy Modeling for GH

Similar to Honeybee, Archsim Energy Modeling is a plugin that brings fully featured EnergyPlus simulations to Rhino/Grasshopper and thus links the EnergyPlus simulation engine with a powerful parametric design and CAD modeling environment. Archsim allows you to effortlessly create complex multi-zone energy models, simulate them and visualize results without ever switching between tools.

Honeybee

Honeybee connects Grasshopper3D to EnergyPlus, Radiance, Daysim and OpenStudio for building energy and daylighting simulation. The Honeybee project intends to make many of the features of these simulation tools available in a parametric way.

UrbanDaylighting

Uses Radiance & daysim to simulate daylighting of large urban designs.

DIVA for Rhino: GH Plugin

DIVA-for-Rhino is a highly optimized daylighting and energy modeling plug-in for Rhino and Grasshopper. DIVA-for-Rhino allows users to carry out a series of environmental performance evaluations of individual buildings and urban landscapes.
**Reinhart Method for Daylighting Simulation**

MIT Lecture: Daylighting Course

Goal: Assess the luminous environment in daylit spaces via simulation.

The scene consists of a three-dimensional geometric model of the investigated daylit object(s) including optical material descriptions for all surfaces in the scene.

Areas of interest in the scene can be selected viewpoints and/or discrete sensors such as a grid of upward facing illuminance sensors.

Space usage information describe the type of space investigated (office, classroom, ...), required lighting levels and occupancy schedules.

The sky model quantifies the amount of direct sunlight and diffuse daylight coming from the different parts of the celestial hemisphere.

The composite model brings all information together into one defined set of data for export to the analysis/simulation engines.

The daylight simulation engine combines the sky model with the scene and calculates illuminances and/or luminances within the scene.

The results processor translates the raw simulation results into a format that can directly inform design decisions. Example formats are scene visualizations and false color maps of the daylight factor and/or other performance metrics including daylight autonomy and useful daylight illuminance.
Reinhart Method Inputs
MIT Lecture: Daylighting Course

Goal: Assess the luminous environment in daylit spaces via simulation.

**Inputs**

**SCENE**
- Geometry
- Landscape
- Reflectance levels
- Materials
- Artificial Lighting
- Shading

**Area of Interest**
- Viewpoint
- Grid of sensor points

**Space Usage**
- Program
- Lighting requirements
- Schedules

**Sky Model**
- Date
- Time
- Location
- Sky condition
- Weather data

Reinhart Example (above):

Scene:
- Skylights: Parametric controls
- Windows: Parametric controls (cannot be changed when skylights are being changed).
- Defined building form (unchangeable).

Area of Interest:
- 14X14 grid per floor = 980 total analysis nodes

Space Usage:
- Weekdays 8am-5pm

Sky Model:
- Indoor daylighting levels under overcast skies (info provided)
The use of a parametric base for analysis/simulation plugins, as well as a new component which facilitates behavioral modeling, would not only further the accuracy of testing the effects of multiple dynamic systems, but become a new tool that merges model, behavior, analysis and simulation to strive for efficient implementation of these technologies and a platform for testing systems’ compensation for introduced variables (bio-responsiveness, enviro-responsiveness, manipulability etc).

**Hypothesis**

The use of a parametric base for analysis/simulation plugins, as well as a new component which facilitates behavioral modeling, would not only further the accuracy of testing the effects of multiple dynamic systems, but become a new tool that merges model, behavior, analysis and simulation to strive for efficient implementation of these technologies and a platform for testing systems’ compensation for introduced variables (bio-responsiveness, enviro-responsiveness, manipulability etc).
This pre-hypothesis flowchart represents the adaption of Christoph Reinhart’s method for daylighting simulation with parametric tools (using Grasshopper primarily instead of creating a singular model for export). Plugins link the data between model and analysis software constantly, so input manipulation is facilitated in terms of getting quick results.

Inputs (below) represent importable standards which work in direct relation to EnergyPlus simulations.
Hypothesis: Behavioral Modeling

Behavioral Modeling is added to the method to accommodate complex system(s) analysis and simulation.

**Inputs**
- SCENE
  - Geometry
  - Landscape
  - Reflectance levels
  - Materials
  - Artificial Lighting
  - Shading
- Area of Interest
  - Viewpoint
  - Grid of lighting/thermal sensor points
- Space Usage
  - Program
  - Lighting requirements
  - Thermal comfort req’s
  - Schedules
- Sky Model
  - Date
  - Time
  - Location
  - Sky condition
  - Weather data
  - Solar Radiation

**Behavioral Modeling**
- Dynamic Systems
  - Technologies which respond to the analysis data
- Behavioral Cues
  - Environmental variables, Dynamic Systems, Occupants
- Behavioral Model
  - Data trees, which contain each ‘frame’ of an action of a changing element

**Model**
- Parametric Model
  - Accumulation of inputs, flexible in accordance with destination software

**Analysis & Simulation**
- Analysis Software
  - EnergyPlus, Radiance, Daysim, EvalGlare
- Daylight Plugins for Grasshopper
  - Honeybee, Ladybug, DIVA, Archsim, UrbanDaylighting
- Thermal/Systems Plugins for Grasshopper
  - Honeybee, Ladybug, Archsim, Geco
- Analysis Software
  - EnergyPlus, OpenStudio, Ecotect

*Visualization or Data*
Behavioral Cues come from many different possible variables:

1. Environmental variables, in relation to other behavioral cues, come into play when measuring a changing system over a period of time.
2. Other dynamic systems might impact the way another system might function. For example, an EDDS facade might have to overcompensate for thermal loads when an automated window system opens up to ventilate the space.
3. Occupant use, for example, might impact the way an EDDS facade changes when people interact with it.

The behavioral model quantifies sets of data from the behavioral cues and the behaviors of the dynamic systems in relation to those cues.

Dynamic systems examples: EDDS (my main focus), automated windows, manipulable lighting/heating/cooling fixtures...

The parametric model replaces the composite model, as data flows received back from plug-ins become parameters which influence a change in either this parametric model, or the behavioral model.

Analysis Software is pretty self explanatory: these are the traditional methods of daylighting/thermal/energy analysis and simulation, which, if functioning on their own, are limited to static (composite) model analyses.

Results are loaded back into Grasshopper as data sets from the plugins (which read the data from Analyses Software). These data sets are usually neatly organized and readable and easily visualized.
Appended Diagram of Inputs

- Model
  - Building/Zones for implementation/analysis
  - Circulation paths for occupant use
  - Egress/Building Codes
  - Degree of slope
  - Ground cover
  - Vegetation/Trees
  - Water
  - Glazing areas
  - Floor/Wall reflectance for diffuse light analysis/glare
  - Construction libraries imported from E+
  - User controllability levels
  - Amount/intensity of lighting systems
  - HVAC
  - Natural ventilation opportunities

- Landscape
  - Analysis on a contextual level
  - Whole-building-analysis scope
  - Zoomed in section of building
  - For whole building/or specified zone

- Materials and Reflectance levels
  - Viewpoint of the area of interest
  - Grid of lighting & thermal sensor points

- Artificial Lighting
  - Use of the spaces
  - Lighting levels required by occupying program
  - Thermal comfort levels required by occupying program
  - Analysis period for simulation
  - Usage schedule, dependent on program typically

- Building Systems
  - Date & Time
  - Location
  - Sky Condition
  - Weather Date:
    - EDDS
      - "pixel" size
      - Non-responsive pattern (optional)
  - Program
    - Lighting requirements:
    - Thermal Comfort Requirements:
    - Schedules:
  - Façade Systems
    - Façade Systems
      - Coverage
      - Manipulability
      - Other automated systems
      - Partitions
      - Manipulatable lighting/thermal/comfort controls
      - Other automated systems
  - Interior Systems
    - Interior Systems
  - Environmental variables
    - Climate variability
    - Wind loads
    - Cloudy-to-sunny transitions
    - Precipitation effects
    - Responsive EDDS
    - Façade/Interior Systems
    - Actions
    - Occupant load
    - Movement

- Area of Interest
  - Manipulability
  - Other automated systems

- Sky Model
  - Manipulatable lighting/thermal/comfort controls
  - Other automated systems

- Dynamic Systems
  - Environmental variables
  - Dynamic Systems
  - Occupants

- Behavioral Cues
  - Sky Model
  - Dynamic Systems
Flowchart of Systems’ Effects

**Old Method**
(disregarding systems)

Environmental Conditions

Daylight Quality/Quantity (illuminance, glare, daylight autonomy etc.)

Building lighting loads & energy requirements

**Current Method**
(simply implementing dynamic systems)

Environmental Conditions

Dynamic facade system mitigates solar radiation/diffuses/redirects daylight

Daylight Quality/Quantity (illuminance, glare, daylight autonomy etc.)

Building lighting loads & energy requirements

**New Method**
(utilizing dynamic systems efficiently)

Environmental Conditions

Dynamic facade system mitigates solar radiation/diffuses/redirects daylight

Daylight Quality/Quantity (illuminance, glare, daylight autonomy etc.)

Also, responds to occupant proximity & occupant's desires for views, light, privacy

Building lighting loads & energy requirements

With Proposed Behavioral Modeling:
Proposed Method

For the aforementioned parametric base, I propose Grasshopper, as it succeeds in combining cross-software plugins, 3D modeling capabilities, custom scripting (Python) if needed, with organized data trees (sets of data which become essential in behavioral modeling). Simulation brings together data from the analysis, 3rd-party programs and the parametric model in Grasshopper, and this data can be used to inform a response among any parametric aspect of the model (one system informing another system, or one system overcompensating for an introduced variable).

To focus my efforts, I will be looking at the analysis/optimization/simulation of technologies implemented in an office tower program in New York City. The dynamic system I will be modeling is an Electroactive Dynamic Display System (EDDS), developed by RPI’s CASE with SOM. For the sake of ease, clarity and recognizability, I will be analyzing the implementation of EDDS on the Seagram Building (following page).
EDDS
Electroactive Dynamic Display System:
Technology to be analyzed

Seagram Building
Testbed for analysis and simulation
### Scale and Depth of Analysis

Overview of the following analyses.

<table>
<thead>
<tr>
<th>Scale</th>
<th>Systems Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban Scale</td>
<td>No EDDS</td>
</tr>
<tr>
<td>Building Scale</td>
<td>No EDDS</td>
</tr>
<tr>
<td>Zoomed-in Scale</td>
<td>No EDDS</td>
</tr>
</tbody>
</table>

#### Urban Scale
- Static EDDS
- Dynamic EDDS

#### Building Scale
- Static EDDS
- Dynamic EDDS

#### Zoomed-in Scale
- Static EDDS
- Dynamic EDDS

Not yet
Scale and Depth of Analysis

Order of the following analyses.

First, the two Urban Scale analyses are shown together to compare results of adding an EDDS-like facade to an entire building.

Second, the building and, third, zoomed-in scale are analyzed without EDDS. Both were analyzed and simulated mainly through the EnergyPlus Software.

Fourth and Fifth are Ecotect-analyzed models, which provides a very limiting amount of information data-wise, but shows the possibilities of behavioral modeling, however simple the analysis may be.
1. Urban Scale, No EDDS

Building+Context Daylighting Analysis

1. Create simplified building mass. At this scale, it would take a long time for the computer to analyze every aspect of a detailed model. Fortunately, the UrbanDaylighting component for grasshopper, which links to DaySim, allows the user to split a mass roughly by floor height/number of floors.

2. Add context/shaders to the model.

3. Run the simulation. This simulation measures the directly daylit area of the Seagram Building without any shading system implemented.

Results: Of the 54990 m² floor area, 7142 m² day-lit
Average 13.0% of floor is directly lit by sun
1. Urban Scale, Staic EDDS

Building+Context Daylighting Analysis with EDDS-like shaders added to the facade.

3. Previously ran no EDDS simulation

Results: Of the 54990 m² floor area,
7142 m² day-lit
Average 13.0% of floor is directly lit by sun

4. Import results from simulation as a set of data, rearrange data on a per-floor basis, model the shading system with the size of each panel (shown in blue) customized relative to the amount of light penetrating the building.

5. Run the simulation a second time.

Results: Of the 54990 m² floor area,
4351 m² day-lit area
Average 7.9% of floor is directly lit by sun
2792 m²/60% direct daylighting decrease from non-EDDS analysis
2. Building Scale Setup

Seagram Building without context or EDDS.

1. Construct model building mass.

2. Set up EnergyPlus Zones based on the scale of the work. In this example, each floor is a zone, which should average out any values of implied zones on a per floor basis.

3. Create inputs for the zones, in this case a generalized glazing ratio representing the actual amount of fenestration on the facade.
2. Building Scale: Analyzed with E+ Seagram Building without context or EDDS.

Analyzing Temperature and Humidity:

**Mean Radiant Temperature**

The mean radiant temperature of each zone (degrees Celsius).

**Relative Humidity**

The relative humidity of each zone (%).

**Operative Temperature**

The mean operative temperature of each zone (degrees Celsius).
2. Building Scale: Analyzed with E+
Seagram Building without context or EDDS.

Analyzing Thermal Energy Loads:

Total Thermal Energy Loads

The total thermal energy used by each zone in kWh. This includes cooling and heating.

Heating Loads

The heating energy needed in kWh. For Ideal Air loads, this is the sum of sensible heat that must be added to each zone. For distributed OpenStudio Systems like Packaged Terminal Heat Pumps (PTHP), this will be electric energy for each zone. For central OpenStudio systems, this output will be a single list for the whole building.

Cooling Loads

The cooling energy needed in kWh. For Ideal Air loads, this is the sum of sensible and latent heat that must be removed from each zone. For distributed OpenStudio systems like Packaged Terminal Heat Pumps (PTHP), this will be electric energy for each zone. For central OpenStudio systems, this output will be a single list for the whole building.
2. Building Scale: Analyzed with E+
Seagram Building without context or EDDS.

Analyzing Solar Radiation:

Total Solar Gains

The total solar gain in each zone (kWh).

Exterior Solar Diffuse Gains

The diffuse solar gain in each zone from exterior windows (kWh).

Exterior Solar Beam Gains

The direct solar beam gain in each zone from exterior windows (kWh).
Analyzing People/Systems:

People Gains

The internal heat gains in each zone resulting from people (kWh).

Electric Equip. Energy Usage

The electric equipment energy needed for each zone in kWh.

Electric Lighting Energy Usage

The electric lighting energy needed for each zone in kWh.
Design zones of the floor to be analyzed in place of proposed/existing rooms. This example has been generalized: 15 zones make up a floor containing 30+ rooms. Specify inputs/presets in accordance with the goal EnergyPlus simulation.
3. Zoomed-in Scale: Analyzed with E+

Seagram Building floor without context or EDDS.

Analyzing Temperature and Humidity:

**Mean Radiant Temperature**

The mean radiant temperature of each zone (degrees Celsius).

**Humidity**

The relative humidity of each zone (%).

**Operative Temperature**

The mean operative temperature of each zone (degrees Celsius).
3. Zoomed-in Scale: Analyzed with E+

Seagram Building floor without context or EDDS.

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3. Zoomed-in Scale: Analyzed with E+

Seagram Building floor without context or EDDS.

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Total Solar Gains

The total solar gain in each zone (kWh).

Exterior Solar Diffuse Gains

The diffuse solar gain in each zone from exterior windows (kWh).

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The direct solar beam gain in each zone from exterior windows (kWh).
3. Zoomed-in Scale: Analyzed with E+
Seagram Building floor without context or EDDS.

Analyzing People/Systems:

**People Gains**

The internal heat gains in each zone resulting from people (kWh).

**Electric Equip. Energy Usage**

The electric equipment energy needed for each zone in kWh.

**Electric Lighting Energy Usage**

The electric lighting energy needed for each zone in kWh.
3. Zoomed-in Scale: Analyzed with E+

Seagram Building floor without context or EDDS.

*Indoor Radiant Temperature Map*

1 meter by 1 meter grid of sensor points each provide a result post-analysis to be merged into an indoor radiant temperature map. Note the corridor penetrating the center of the building (with the least amount of area-to-glazing ratio). The cooler sensory points at the north corner of the building may be an anomaly, or an accurate representation of the cooler north-side zones.
3. Preliminary Results - No EDDS

Looking at the results of a section of the Seagram Building

Diagram of results mapped out over time

EnergyPlus provides results on a zone-by-zone basis, with data for each zone representable for every hour of the year (in this case, an averaged total hourly thermal energy required per zone per m² per month per year).
4. Building & Zoomed-in Scale

Seagram Building and building section analyzed with a static instance of EDDS implemented.

Building Scale Analysis

Seagram Building typical direct/diffuse daylighting levels analyzed without contextual influence. One instance of a non-moving EDDS facade is analyzed.

Zoomed-in Analysis

Test of daylighting analysis in a space with two EDDS-like partitions. Context and building are not taken into account. This study represents an instance of light diffusing around temporary or potentially moving EDDS obstructions.
Behavioral Modeling - My Proposal

Part 5 looks at applying a dynamic system to a building and building section, and analyze each's impact on the space.
5. Building Scale & Zoomed-in Analysis

**Seagram Building** Test building and zoomed-in model analyzed with a dynamic instance of EDDS implemented.

**Building Scale Analysis**

Composite analysis of 5 facade iterations, meant to simulate EDDS movement.

**Zoomed-in Analysis**

Behavior: Person walking in front of responsive EDDS facade. 7 points along the way compiled into a composite analysis.
What could a dynamic system, such as EDDS compensate for in a space/building?

- Heat/Cooling/Lighting gains due to:
- Increase of Occupants
- Changing weather patterns
- An influx of machines in a space (computers etc)
- Changing thermal properties on nearby floors/in nearby zones
- More…

**Analysis with no EDDS**

Results: Of the 54990 m² floor area, 7142 m² day-lit
Average 13.0% of floor is directly lit by sun

**EDDS responding to areas of too much direct lighting**

After the first simulation, the results are read and the new model rebuilds itself to accommodate the results: to lessen direct daylighting loads.

**Resultant simulation**

Results: Of the 54990 m² floor area, 4351 m² day-lit area
Average 7.9% of floor is directly lit by sun
2792m²/60% direct daylighting decrease from non-EDDS analysis
What could a dynamic system, such as EDDS compensate for in a space/building?

- Heat/Cooling/Lighting gains due to:
- Increase of Occupants
- Changing weather patterns
- An influx of machines in a space (computers etc)
- Changing thermal properties on nearby floors/in nearby zones
- More…
Analysis Speculation:

Example: Mean Radiant Temp Analysis

The mean radiant temperature of each zone (degrees Celsius).

Result diagram key: Color key:

No EDDS/Shaders - Actual Analysis

A representation of the average radiant temperature in all zones over the span of a year (monthly values are determined from hourly results). Clearly the simulation shows that there is a rise in temperature during the summer months as is expected.

Static Instance of EDDS - Speculation

Implementing any shading device, including a static instance of EDDS, would result in a decrease of average radiant temperatures during the summer months.

Dynamic/Responsive EDDS - Speculation

Moving beyond static shading devices, however, we get into the territory of responsive systems. I speculate an improvement in average temperature during summer months with the implementation of a fully dynamic EDDS system. In this case, EDDS would respond to occupant movement, other systems, environmental cues etc.
Moving Forward

I hope to further develop a method for analyzing and simulating complex building systems in architecture. This method for analysis and optimization would facilitate the efficient implementation of dynamic/advanced/sustainable technologies in all building typologies.
Proposal: A New Grasshopper Component

The main potential of this research, I feel, is to create a method for implementing and analyzing dynamic systems in design. The proposal for bringing behavioral modeling into the parametric design realm might best be captured by creating a new Grasshopper component which facilitates this idea.

This component would separate dynamic input into data sets readable by EnergyPlus & Radiance.
Bibliography:


Modeling and Analyzing Unpredictable Building Systems
Real-Time Whole Building Performance Impacts of Occupant Interaction with Dynamic Façade Systems
Problems:
Current tools don’t support analyzing unpredictable systems’ effects on buildings.

Building performance analyses are usually centered around static resultant data and they don’t necessarily account for unpredictable human behavior.

I contend:
By developing a new workflow that links energy analysis tools to parametric modeling tools which can represent human behavior, we can better design and implement new building facade technologies that deal with a broader range of architectural performance criteria.

• Introduction
  • Contention
• Dynamic Facade Systems
• Analysis Inputs
• The Method
• Software Used
• The Building Testbed
• Single Zone Analysis
• Multiple Zone Analysis
• Building Visualizations
• Conclusions
Part 1:
Project Background
Dynamic Glazing Systems

- Introduction
- Dynamic Facade Systems Examples
- Analysis Inputs
- The Method
- Software Used
- The Building Testbed
- Single Zone Analysis
- Multiple Zone Analysis
- Building Visualizations
- Conclusions
Dynamic Glazing Systems
Example 1
The Arab World Institute
by Jean Nouvel

- Introduction
- Dynamic Facade Systems
  Arab World Institute
- Analysis Inputs
- The Method
- Software Used
- The Building Testbed
- Single Zone Analysis
- Multiple Zone Analysis
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- Conclusions
Dynamic Glazing Systems
Example 2
Syracuse Center of Excellence
by Toshiko Mori

- Introduction
- Dynamic Facade Systems
  Center of Excellence
- Analysis Inputs
- The Method
- Software Used
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- Single Zone Analysis
- Multiple Zone Analysis
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Dynamic Glazing Systems
Example 3
Homeostatic Facade System
by Decker Yeadon LLC

- Introduction
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Dynamic Glazing Systems
Example 4
Electroactive Dynamic Display System (EDDS)
by the Center for Architecture Science and Ecology

- Introduction
- Dynamic Facade Systems
  EDDS
- Analysis Inputs
- The Method
- Software Used
- The Building Testbed
- Single Zone Analysis
- Multiple Zone Analysis
- Building Visualizations
- Conclusions
**Dynamic Glazing Systems Example 4 Continued**

**EDDS details**

**Patent #: US 8,134,112 B2**

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  - Conclusions

- Contained within an IGU
- Switches (rolls) easily
- Default position is up
- Low cost to fabricate/operate
- ~$10-$80 per ft² (electrochromic glass is $100+ per ft²)
- High voltage, low current system

Accommodates:
- Solar tracking
- Glare/Daylighting control
- Design variability
- Occupant interaction
- Much more...

- Glass Substrate
- Transparent Fixed Electrodes
- Transparent Dielectric Layer
- Adhesive Glue
- Anchor Lines
- Movable Electrode
- Rolled Metalized Polymer
  - possibility for multiple layers

- Contained within an IGU
- Switches (rolls) easily
- Default position is up
- Low cost to fabricate/operate
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Accommodates:
- Solar tracking
- Glare/Daylighting control
- Design variability
- Occupant interaction
- Much more...
**Dynamic Glazing Systems**

**Example 4 Continued**

EDDS visualization

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Dynamic Glazing Systems
Example 4 Continued
Occupant Viewing & Privacy Screens

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Example 4 Continued
Occupant Interaction

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Dynamic Glazing Systems
Example 4 Continued
System Compensation

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The Traditional Building Analysis
C. Reinhart’s Daylighting Analysis Example

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  - Current Method Used
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The Method for Complex Building System Analysis
Amending the Traditional Model

**Inputs**

- **SCENE**
  - Geometry
  - Landscape
  - Reflectance levels
  - Materials
  - Artificial Lighting
  - Shading

- **Area of Interest**
  - Viewpoint
  - Grid of lighting/thermal sensor points

- **Space Usage**
  - Program
  - Lighting requirements
  - Thermal comfort req’s
  - Schedules

- **Sky Model**
  - Date
  - Time
  - Location
  - Sky condition
  - Weather data
  - Solar Radiation

**Responsive Inputs**

- **Dynamic Systems**
  - Technologies which respond to occupants, other stimuli

- **Occupant Interaction**
  - Proximity & Position
  - View Preference
  - Privacy
  - Gestures

- **Design Variables**
  - Pattern Preferences
  - Information Display
  - Visual Effects

**Model**

- **Parametric Model**
  - Accumulation of inputs & result data

**Analysis & Simulation**

- **Single-Zone Analysis Software**
  - EnergyPlus, Radiance, Daysim, EvalGlare

- **Daylight Plugins for Grasshopper**
  - DIVA, Honeybee, Ladybug, Archsim, UrbanDaylighting

- **Thermal/Systems Plugins for Grasshopper**
  - Honeybee, Ladybug, Archsim, Geco

- **Multi-Zone Analysis Software**
  - EnergyPlus, OpenStudio, Ecotect
The Method for Complex Building System Analysis
The Feedback Loop

Inputs
- SCENE
  - Geometry
  - Landscape
  - Reflectance levels
  - Materials
  - Artificial Lighting
  - Shading
- Area of Interest
  - Viewpoint
  - Grid of lighting/thermal sensor points
- Space Usage
  - Program
  - Lighting requirements
  - Thermal comfort req's
  - Schedules
- Sky Model
  - Date
  - Time
  - Location
  - Sky condition
  - Weather data
  - Solar Radiation

Responsive Inputs
- Dynamic Systems
  - Technologies which respond to occupants, other stimuli and analysis data
- Occupant Interaction
  - Proximity & Position
  - View Preference
  - Privacy
  - Gestures
- Design Variables
  - Pattern Preferences
  - Information Display
  - Visual Effects

Model
- Parametric Model
  - Accumulation of inputs & result data

Analysis & Simulation
- Single-Zone Analysis Software
  - EnergyPlus, Radiance, Daysim, EvalGlare
- Daylight Plugins for Grasshopper
  - DIVA, Honeybee, Ladybug, Archsim, UrbanDaylighting
- Thermal/Systems Plugins for Grasshopper
  - Honeybee, Ladybug, Archsim, Geco
- Multi-Zone Analysis Software
  - EnergyPlus, OpenStudio, Ecotect
**Software Tools**

All programs that can be linked into this method

3D Modeling Platform:
- Rhinoceros

Parametric Modeling Platform:
- Grasshopper

Analysis Plugins:
- Honeybee
- Ladybug
- DIVA
- ArchSim
- UrbanDaylighting
- Geco

Analysis Software:
- EnergyPlus
- OpenStudio
- Radiance
- DaySim
- DaySim
- EvalGlare
- EcoTect

- Introduction
- Dynamic Facade Systems
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  - Linkages
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The Building

1095 Ave. of the Americas

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- Software Used
- The Building Testbed
  - Why the tower?
- Single Zone Analysis
- Multiple Zone Analysis
- Building Visualizations
- Conclusions
Part 2: Building Analyses

1: Single Zone Scale

2: Multiple Zone Scale
Single-Zone Analysis
Single-Zone Analysis

Intro

Daylighting Analysis

Animation

Daylighting Infiltration %

- 0%
- 30%

- Introduction
- Dynamic Facade Systems
- Analysis Inputs
- The Method
- Software Used
- The Building Testbed
- **Single Zone Analysis**
  - [Intro to Daylighting Analysis](#)
- Multiple Zone Analysis
- Building Visualizations
- Conclusions
Single-Zone Analysis

Intro

Daylighting Analysis

Animation

- Introduction
- Dynamic Facade Systems
- Analysis Inputs
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- Software Used
- The Building Testbed
- Single Zone Analysis
  - Intro to Daylighting Analysis
- Multiple Zone Analysis
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- Conclusions
Single-Zone Analysis
#1
1 zone daylighting analysis
NO EDDS

Average Daylighting = 7.49%
Single-Zone Analysis
#2
1 zone daylighting analysis
NON-RESPONSIVE EDDS

- Introduction
- Dynamic Facade Systems
- Analysis Inputs
- The Method
- Software Used
- The Building Testbed
- Single Zone Analysis
  Non-Responsive EDDS
- Multiple Zone Analysis
- Building Visualizations
- Conclusions

Average Daylighting = 4.60%
Single-Zone Analysis
#3
1 zone daylighting analysis
RESPONSIVE EDDS

- Introduction
- Dynamic Facade Systems
- Analysis Inputs
- The Method
- Software Used
- The Building Testbed
- Single Zone Analysis
  - Responsive EDDS
- Multiple Zone Analysis
- Building Visualizations
- Conclusions

Average Daylighting = 5.98%

Daylighting Infiltration %

<table>
<thead>
<tr>
<th></th>
<th>0%</th>
<th>30%</th>
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<tr>
<td>No EDDS</td>
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<tr>
<td>Responsive EDDS</td>
<td>5.98</td>
<td>7.49</td>
</tr>
<tr>
<td>Responsive EDDS (portals)</td>
<td>4.60</td>
<td></td>
</tr>
</tbody>
</table>
Single-Zone Analysis #4
1 zone daylighting analysis
COMPENSATING EDDS

Average Daylighting = 4.46%

Daylighting Infiltration %
0% 30%

- Introduction
- Dynamic Facade Systems
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- The Building Testbed
- Single Zone Analysis
  Compensating EDDS
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Multi-Zone Analysis
Intro

Scale of Analysis

- Introduction
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- Analysis Inputs
- The Method
- Software Used
- The Building Testbed
- Single Zone Analysis
- **Multiple Zone Analysis**
  - Intro
  - Building Visualizations
  - Conclusions
Multi-Zone Analysis

1. Thermal Energy Requirements
2. Interior Air Temperature
3. Mean Radiant Temperature
4. Radiant Heat Map

Zonal Energy Flux:
Mapping thermal energy passing through interior walls between spaces

- Introduction
- Dynamic Facade Systems
- Analysis Inputs
- The Method
- Software Used
- The Building Testbed
- Single Zone Analysis
- Multiple Zone Analysis
  - No EDDS
- Building Visualizations
- Conclusions
Multi-Zone Analysis
#3
28 zones analyzed with NON-RESPONSIVE EDDS

1. Thermal Energy Requirements
   - Avg. 40 kwh/m²/yr

2. Interior Air Temperature
   - Avg. 21°C

3. Mean Radiant Temperature
   - Avg. 20°C

4. Radiant Heat Map
   - 18°C

Zonal Energy Flux:
Mapping thermal energy passing through interior walls between spaces
Multi-Zone Analysis

28 zones analyzed with RESPONSIVE EDDS

1. Thermal Energy Requirements
- Cooling: Avg. 70 kwh/m²/yr
- Heating: Avg. 60 kwh/m²/yr

2. Interior Air Temperature
- Avg. 21°C

3. Mean Radiant Temperature
- Avg. 22°C

4. Radiant Heat Map
- Avg. 22°C

Zonal Energy Flux:
Mapping thermal energy passing through interior walls between spaces

- Cooling: 0 kwh/m²
- Heating: 100 kwh/m²
Multi-Zone Analysis

#4

28 zones analyzed with COMPENSATING EDDS

1. Thermal Energy Requirements

   - 100 kwh/m²/yr Cooling
   - 100 kwh/m²/yr Heating

2. Interior Air Temperature

3. Mean Radiant Temperature

4. Radiant Temperature Map

- Avg. 80 kwh/m²/yr
- Avg. 20°C
- Avg. 20°C
- Avg. 40 kwh/m²/yr

Zonal Energy Flux:
Mapping thermal energy passing through interior walls

- Avg. 80 kwh/m²/yr
- Avg. 20°C
Multi-Zone Analysis

RESULTS for 28 Adjacent Zones

- Introduction
- Dynamic Facade Systems
- Analysis Inputs
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- Software Used
- The Building Testbed
- Single Zone Analysis
- **Multiple Zone Analysis Results**
- Building Visualizations
- Conclusions
Part 3: Building Visualizations
Building Visualizations

Seagram Concept Facade with Daylighting Analysis
Building Visualizations

Institute of Contemporary Art

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  Institute of Contemporary Art
- Conclusions
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Seattle Public Library

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British Museum

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Indianapolis Airport

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5th Ave. Apple Store

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Prada Museum

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  - Prada Museum
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Chicago Art Institute

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- Building Visualizations
  Chicago Art Institute
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Building Visualizations

Center of Excellence

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- Multiple Zone Analysis
- Building Visualizations
  - Center of Excellence
- Conclusions
Highly responsive systems can dramatically reduce building energy consumption, improve the well-being of occupants, and explore the architectural design potential of programmable material technologies.

The methods presented provide significant opportunities for combining the design and analysis process to support the integration of next-generation dynamic façade systems.

The ability to support real-time analysis of complex building systems in the design phase reduces the risk of blind implementation that could lead to inefficiency.

It also encourages investment into multifunctional ecological building systems that promote participatory occupant engagement while offering a wide range of architectural design possibilities.