Iowa State University
College of Engineering | Dept. of Civil Construction and Environmental Engineering

Automating the Balance of Energy Performance with Occupant Comfort with Smart Fenestrations

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BACKGROUND

B.S. Civil Engineering

University of Maryland, College Park

M.S. Civil Engineering

University of Maryland, College Park

Ph.D. Civil & Architectural Engineering

University of Texas at Austin

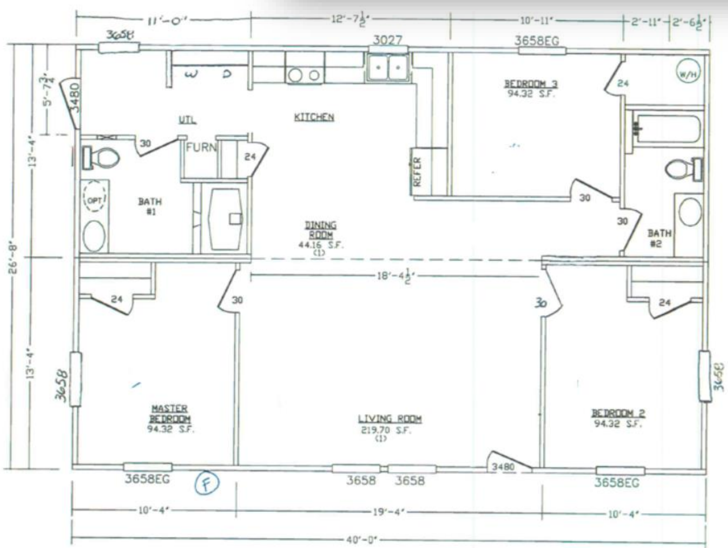
Staff Engineer, P.E., LEED BD+C

Simpson Gumpertz & Heger

Research Associate

National Renewable Energy Lab

RESEARCH LAB: *Smart Building Test Facilities*



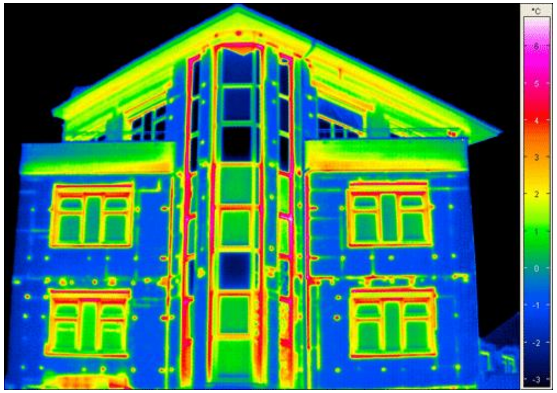
2 identical 1,100 sq ft buildings

Whole-building and submetering capabilities for 30+ circuits per building
Built to current IECC 2015 standards

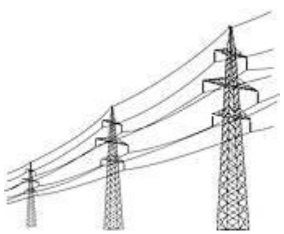
Adjustable interior and envelope features based on research needs

Internal load automation

RESEARCH GOALS



Building Science & Technology



Smart & Connected Technologies, IoT & Data

Buildings

Energy Efficient

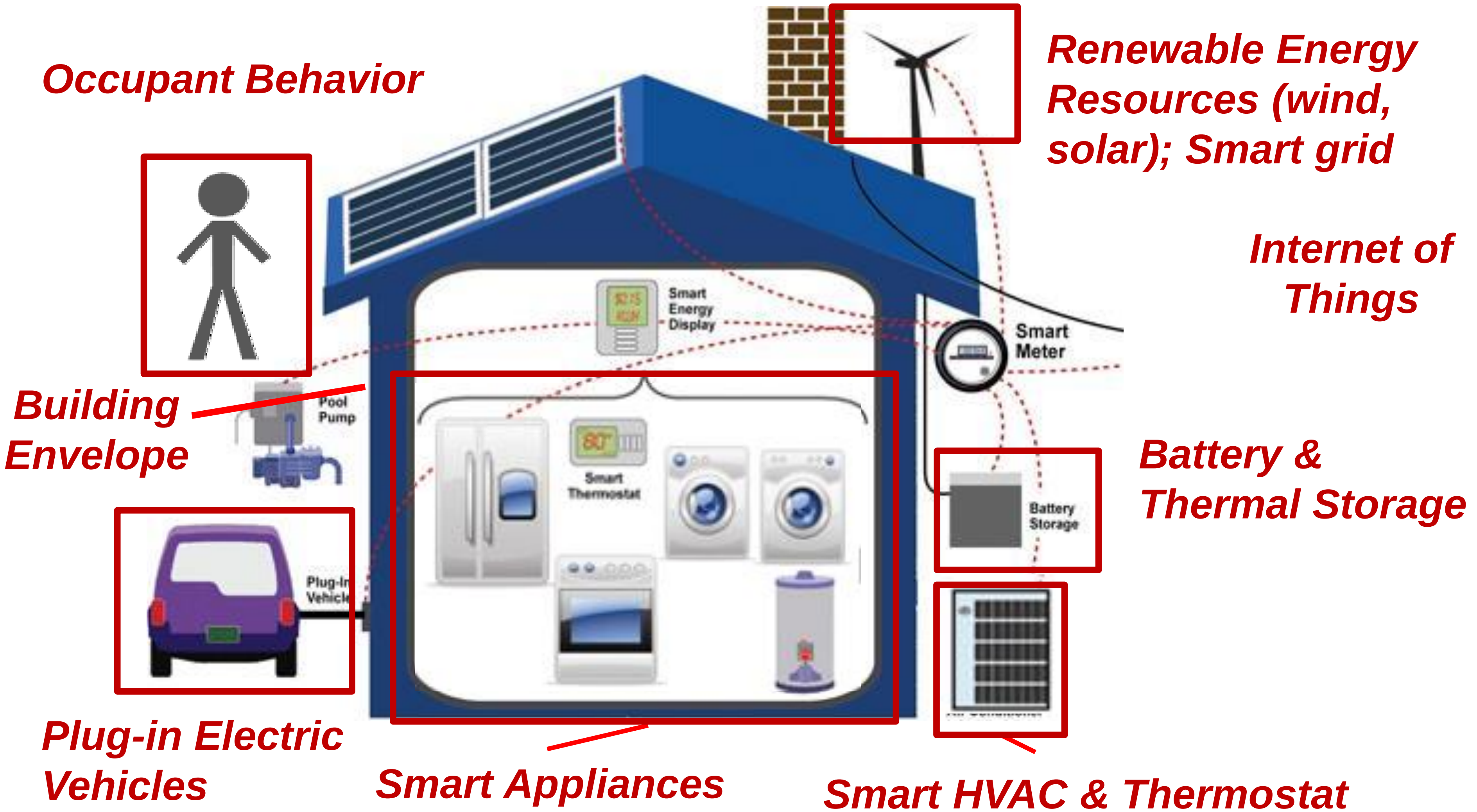
Flexible

Healthy, Productive

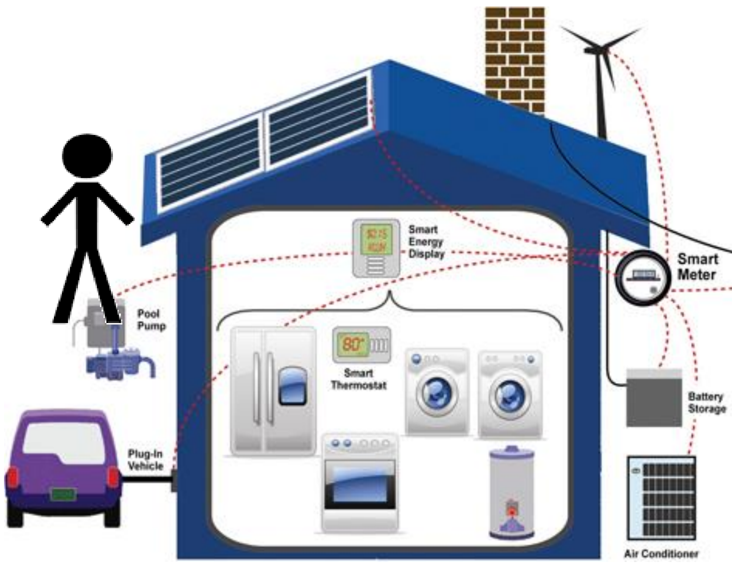
Long-Lasting / Durable

Resilient

SMART BUILDINGS: *Components & Interactions*



FUNDED & ONGOING RESEARCH: *Towards Smarter Infrastructure Systems*



A Framework for Assessing the Impact of Extreme Heat and Drought Climate Scenarios on Urban Energy Production and Consumption

Effects of Dynamic Shading Devices on Daylighting and Energy Performance of Office Perimeter Zones

Adaptive, Multi-Layered Fenestration Elements for Optimum Building Energy Performance and Occupant Comfort

Simulation, Challenge Testing & Validation of Occupancy Recognition and CO2 Technologies

Data-Driven Modeling for Energy Use Predictions, Disaggregation and Energy Efficiency Evaluation of Residential Buildings

Residential Energy Efficiency Investment Behaviors and Non-Energy Benefits

Impact Of Utilizing Electric Ground Power Systems On Airport Electricity Demand Profile

Automating the Balance of Energy Performance with Occupant Comfort with Smart Fenestrations

Effects of Dynamic Shading Devices on Daylighting and Energy Performance of Office Perimeter Zones

ASHRAE

Adaptive, Multi-Layered Fenestration Elements for Optimum Building Energy Performance and Occupant Comfort

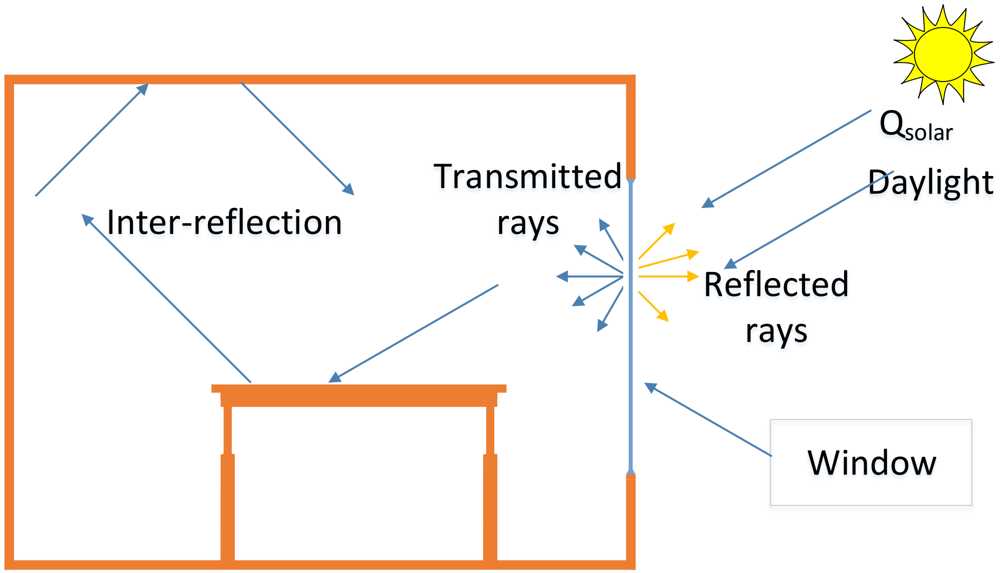
NSF

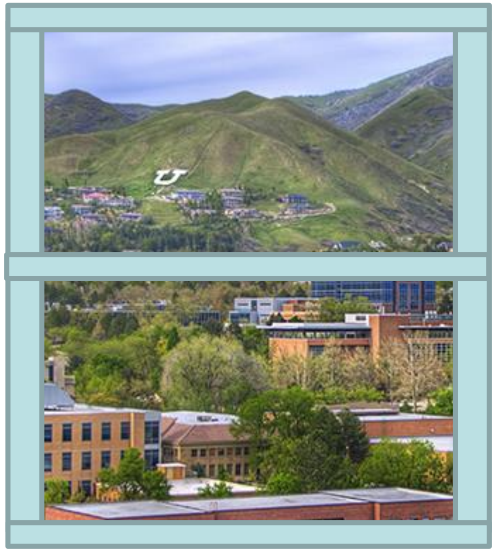
MOTIVATION: *Impacts of Windows on Building Energy Use & Demands*

2.15 Quads of heating energy demand

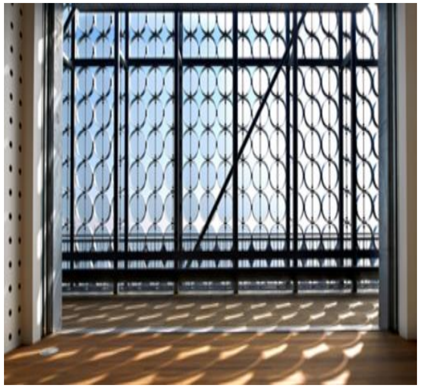
1.42 Quads of cooling energy demand

Impacts on **Visual Comfort** and **Thermal Comfort & Occupant Satisfaction (Views)**



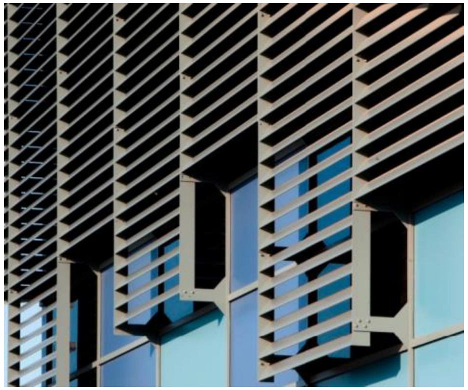


MOTIVATION: *Types of Shading Devices*



Roller Shades

Blinds



GOALS: *Dynamic, Automated Shading Devices*

Goals:

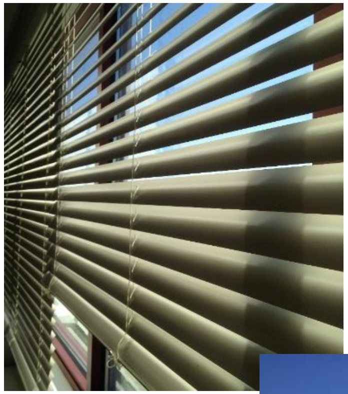
- **Autonomously** control the roller shades or venetian blinds based on sensor and data **feedback**
- **Reduced energy consumption** & energy **demands**
- Maintain occupant **thermal comfort**
- Maintain occupant **visual comfort**

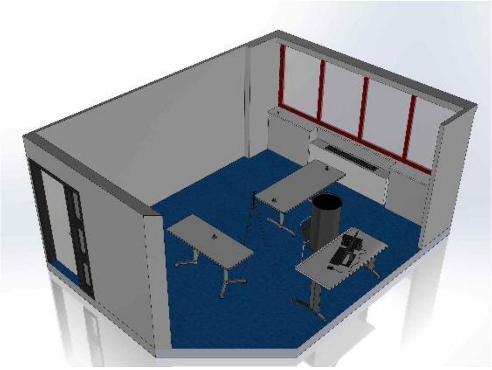
METHODOLOGY:

Control Strategy & Automation Development

Full-Scale Testing and Data Collection

Calibrated Building Energy & Daylight Simulation





EXPERIMENTAL DESIGN: *Shading Devices*

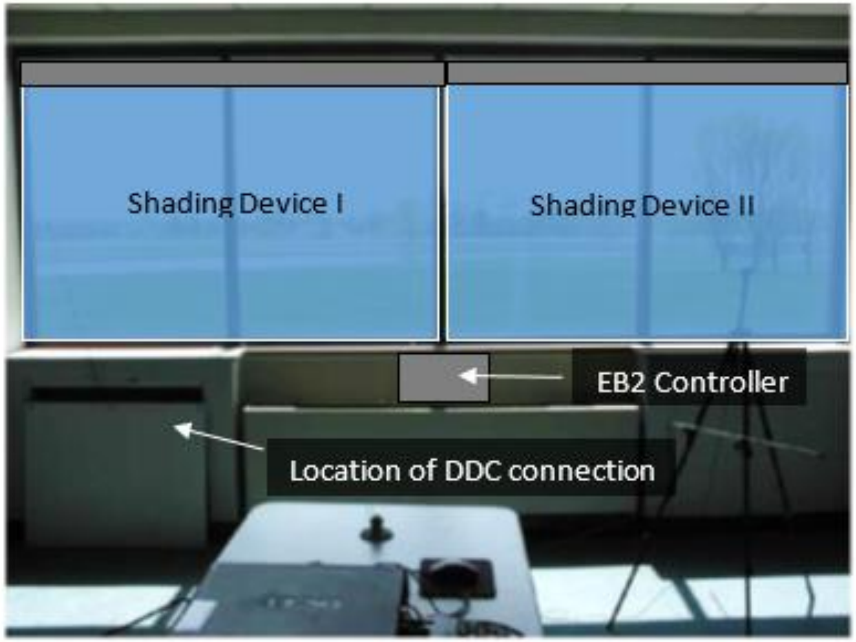
Three types of shading devices:

2 roller shades (Draper - Phifer Sheer Weave)

Shades	**Openness Factor**	**Visible Transmittance**	**Solar Transmittance**	**Solar Absorptance**	**Solar reflectance**	**Color**
Roller Shades 1	1 % (approx.)	1%	1%	95%	4%	Charcoal
Roller Shades 2	3% (approx.)	12%	17%	19%	64%	Oyster

Shades	**Slat Size**	**Material**	**Tilt Angle**	**Solar Reflectance**	**Emissivity**	**Color**
Blinds	2 in	Aluminum	-90 to 90	70%	0.76	Beige

EXPERIMENTAL DESIGN: *Shading Devices*



Motors for device automation

Shading Device	Motor
Roller Shades 1	Sonesse 506
Roller Shades 2	Sonesse 506
Venetian Blinds	Somfy ST40 Sonesse PA-Wired

Controller

Product Name	Vendor	Model No	BACnet Protocol Revision
EB-2 controller	Embedia Technologies Corp.(Vin 252)	1105001	135-2004

EXPERIMENTAL DESIGN: *Test Rooms*

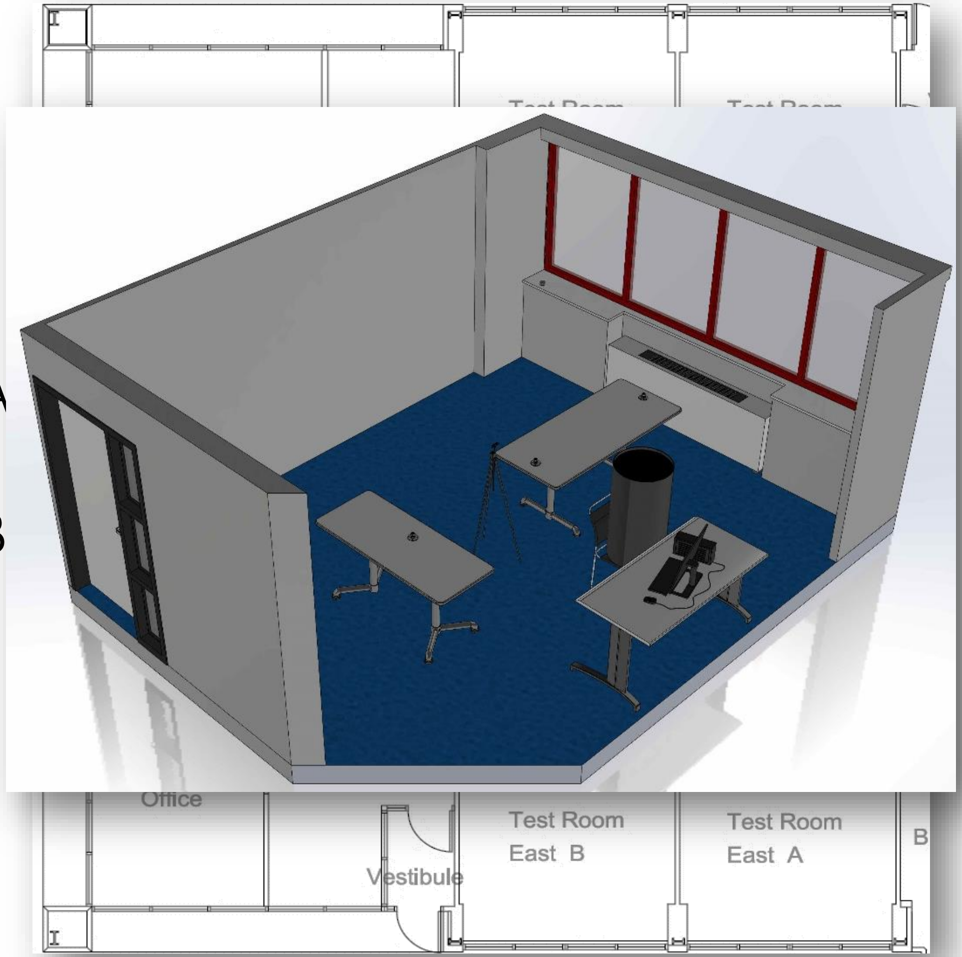
6 exterior identical test rooms

2 each in East, South and West direction

Test rooms A: Air Handling Unit A

Test rooms B: Air Handling Unit B

Each test rooms A and B equipped with variable air volume (VAV) box terminal



EXPERIMENTAL DESIGN

Test Room	Orientation	Glazing[a]	Shading Device[b]		
			Test 1	Test 2	Test 3
A	East	Gl-A	SD-A	SD-B	SD-C
B	East	Gl-B	SD-A	SD-B	SD-C
A	South	Gl-A	SD-C	SD-A	SD-B
B	South	Gl-B	SD-C	SD-A	SD-B
A	West	Gl-A	SD-B	SD-C	SD-A
B	West	Gl-B	SD-B	SD-C	SD-A

Multiple seasons

3 shading devices
(2 roller shades, 1 blinds)

3 orientations
(east, south, west)

2 window types
(clear, low-e)

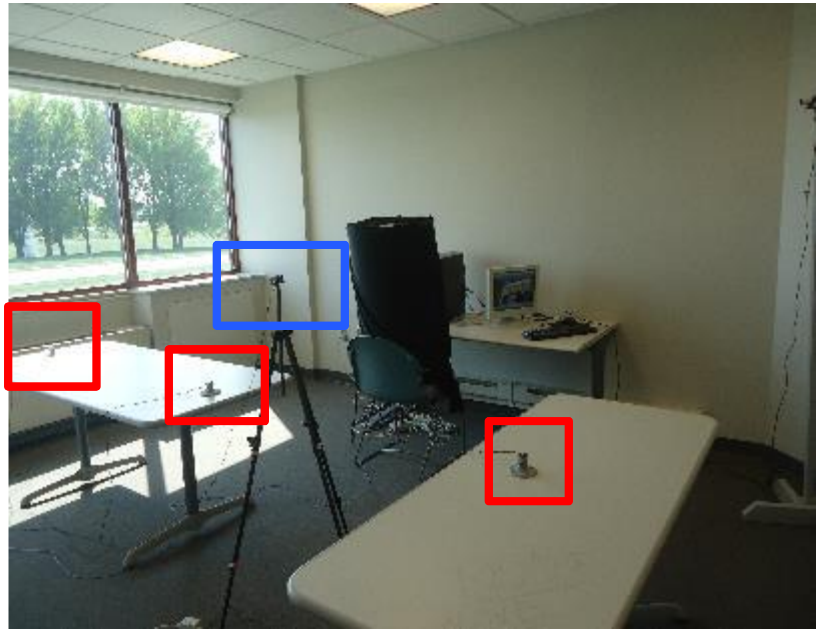
2 control strategies

3 different sky conditions
(sunny, overcast, cloudy)

EXPERIMENTAL DESIGN: *Test Set Up*

Illuminance sensor placement

Sensor	Height from floor	Distance from window
Work plane illuminance	0.76 m	1 m, 2.5 m, 4 m
Vertical illuminance	1.2 m	3 m
Ceiling illuminance sensor	2.56 m	2.86 m



Illuminance sensor placement

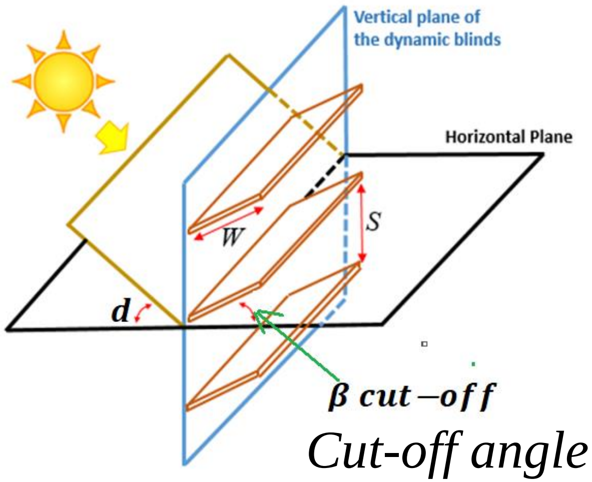
EXPERIMENTAL DESIGN: *Shading & Lighting Control*

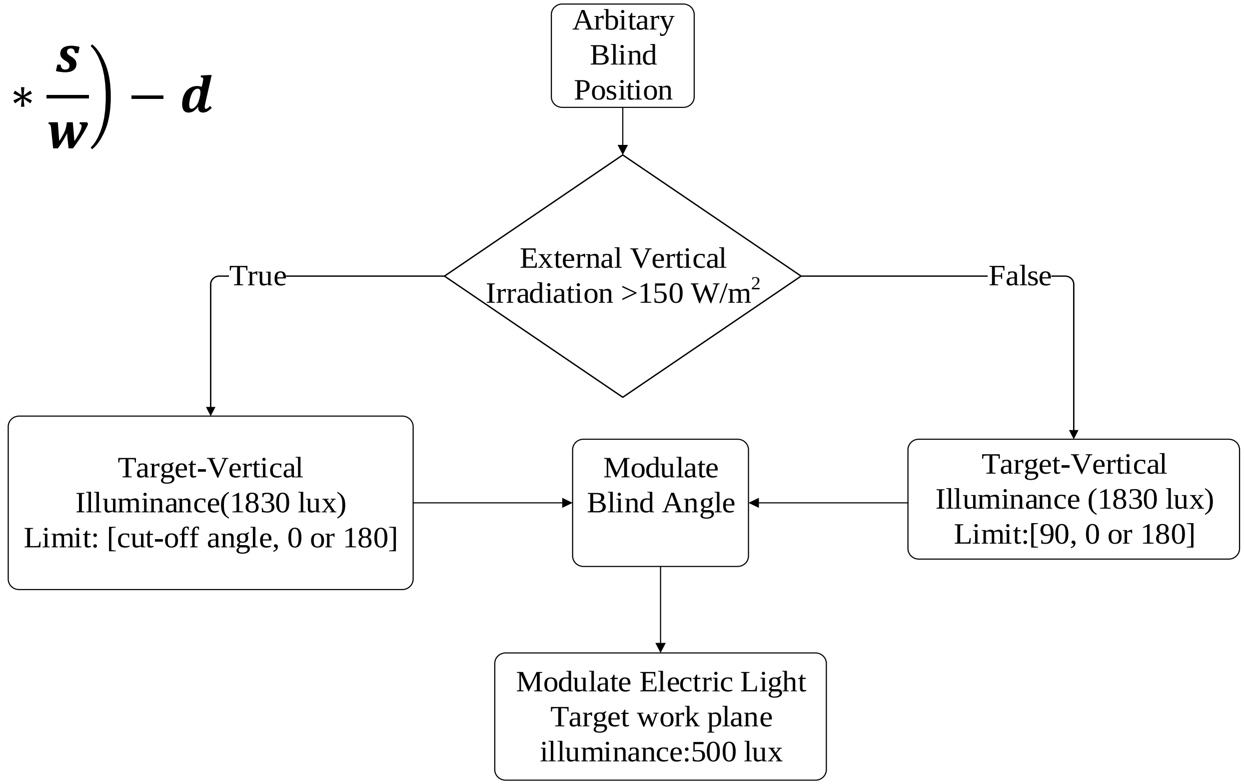
Control Strategy 1 (CS1)

Cut-off angle control

$$\beta_{cut-off} = sin^{-1}\left(cos(d) * \frac{s}{w}\right) - d$$

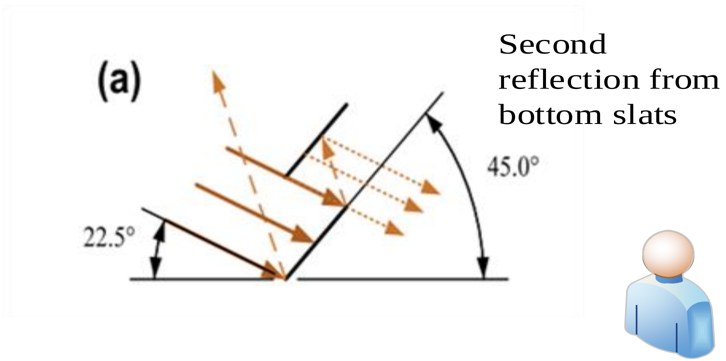
$$d = tan^{-1}\left[\frac{tan(\alpha)}{cos(\gamma)}\right]$$

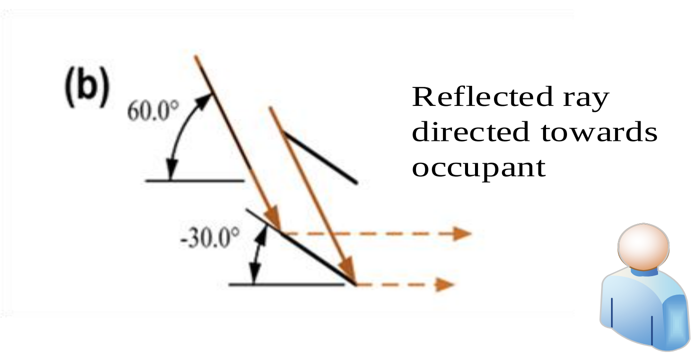


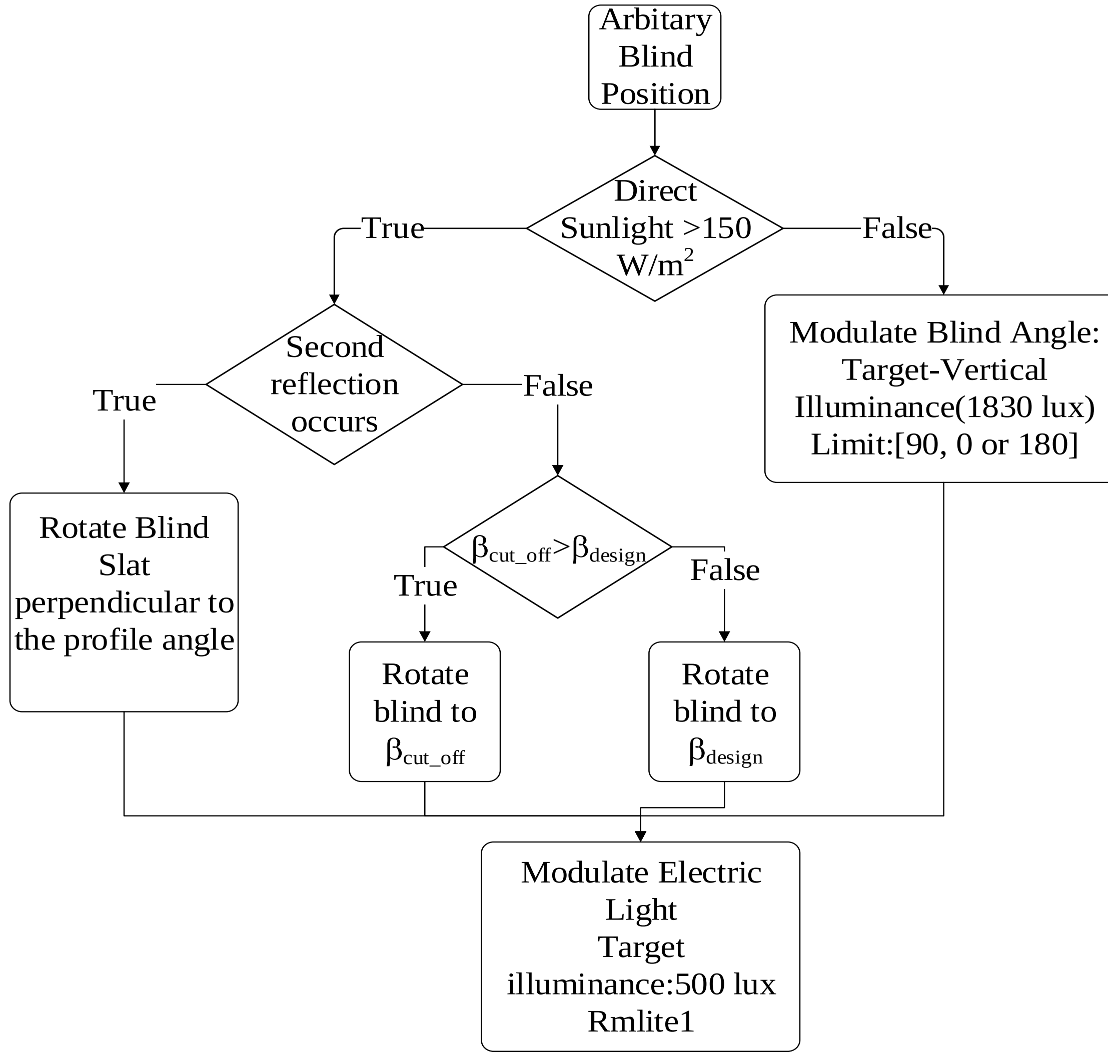


EXPERIMENTAL DESIGN: *Shading & Lighting Control*

Control Strategy 2 (CS2)







RESULTS: *Full-scale Testing Energy Savings*

Orientation	Rotation	Shading Device	Control Strategy	Lighting Energy (kWh)		Percentage Savings (%)
				Test Room A	Test Room B	
East	1	RS (1% VT)	1	37.41	22.49	39.89
			2	29.67	17.29	41.74
	2	RS (12% VT)	1	31.62	16.97	46.34
			2	31.61	15.69	50.36
	3	VB	1	46.92	23.46	50.00
			2	47.06	25.17	46.51
South	1	VB	1	19.06	10.63	44.21
			2	16.03	8.08	49.61
	2	RS (1% VT)	1	37.11	18.31	50.66
			2	26.57	12.49	53.00
	3	RS (12% VT)	1	36.69	17.20	53.13
			2	31.49	14.64	53.51
West	1	RS (12% VT)	1	33.65	21.71	35.46
			2	28.49	17.72	37.79
	2	VB	1	34.38	18.84	45.20
			2	45.59	24.71	45.80
	3	RS (1% VT)	1	40.91	19.84	51.50
			2	40.92	20.33	50.32

CS1 = control strategy 1, CS2 = control strategy 2, RS = roller shades, VB= venetian blinds

RESULTS: *Full-scale Testing Energy Savings*

Lighting energy savings:

40% - 60%

More variability for venetian blinds vs. roller shades

Control strategies, orientations = similar savings

Lower for overcast days vs. sunny/cloudy days

RESULTS: *Full-scale Testing Energy Savings*

Average **lighting** energy saving

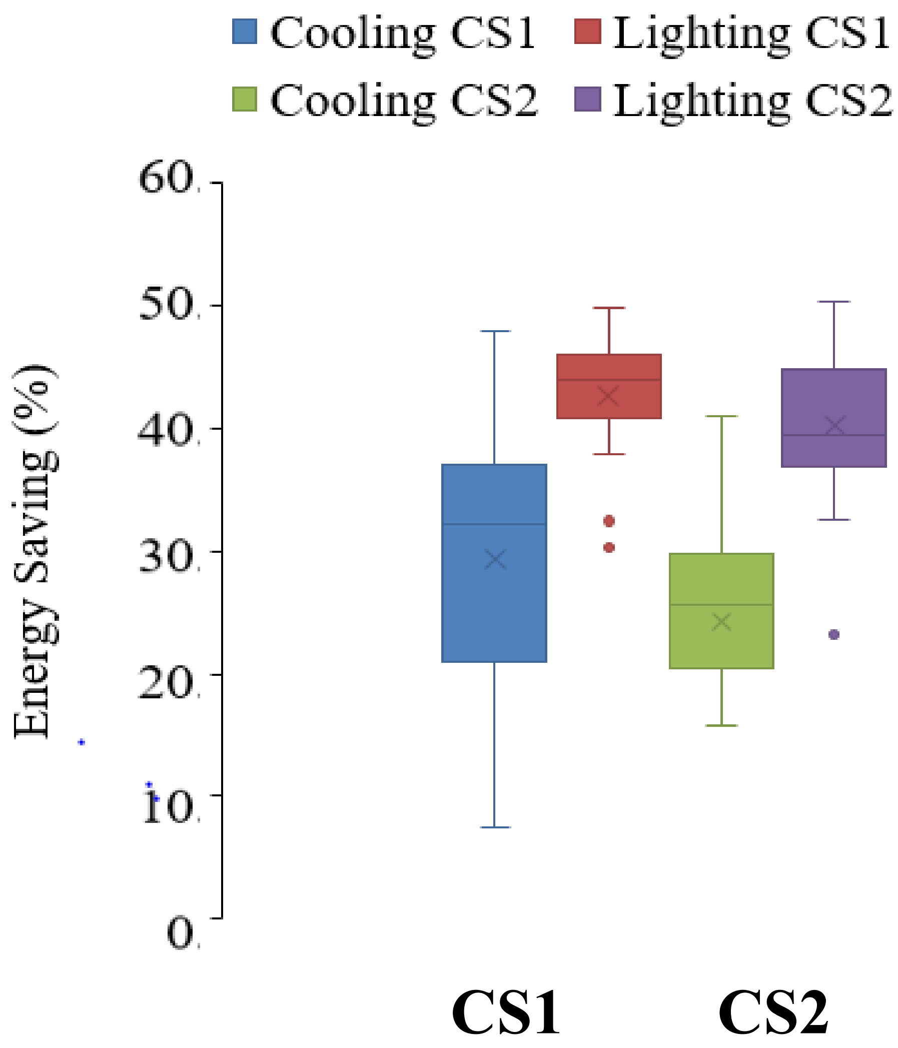
CS1: 42.7 %

CS2: 40.2%

Average **cooling** energy saving

CS1: 29.3%

CS2: 24.2%



RESULTS: *Full-scale Testing Energy Savings*

Lighting energy savings:

40% - 60%

More variability for venetian blinds vs. roller shades

Control strategies, orientations = similar savings

Lower for overcast days vs. sunny/cloudy days

HVAC energy savings:

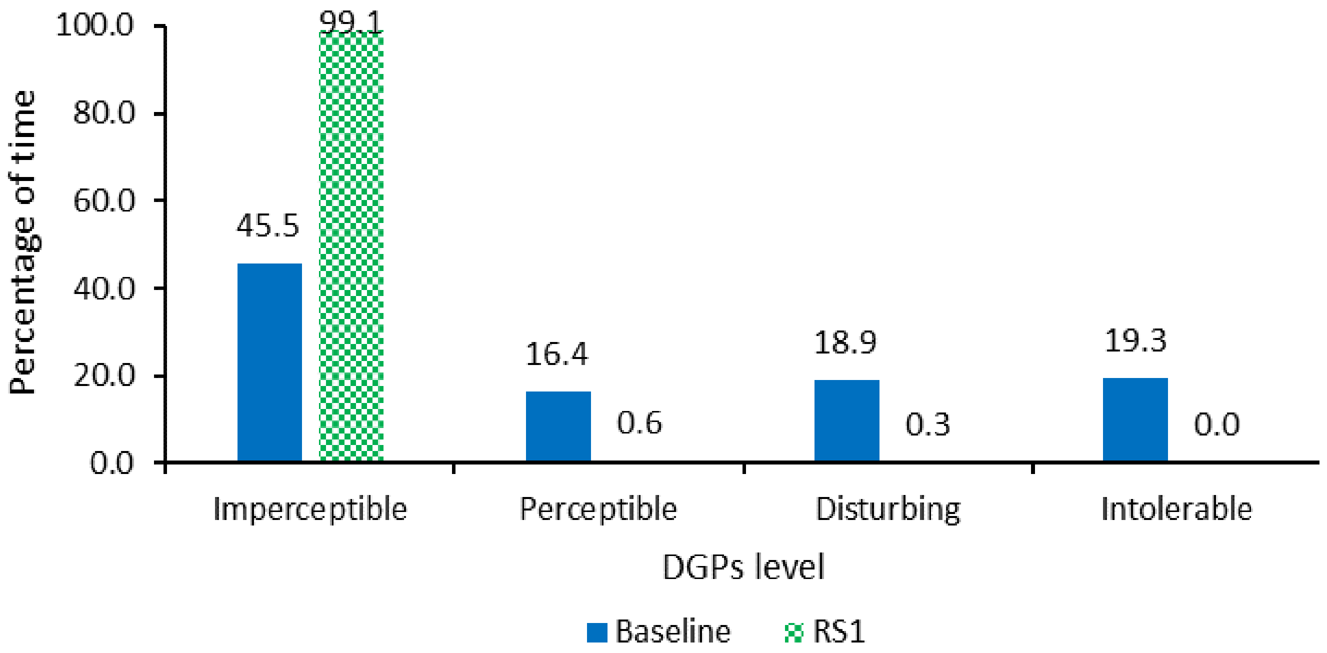
20% - 30%

higher total energy savings compared to lighting

RESULTS: *Full-scale Testing Visual Comfort*

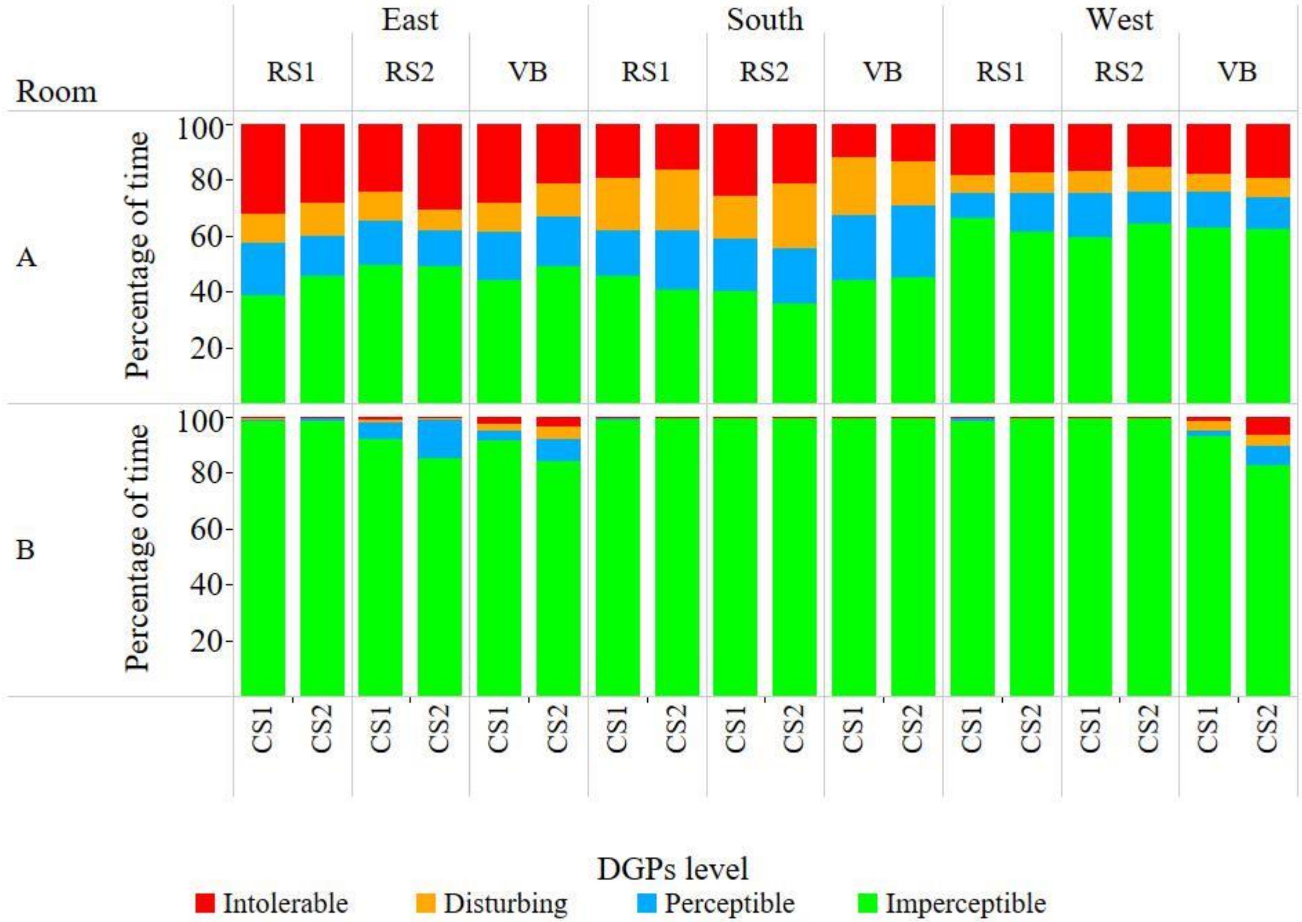
Daylight Glare Probability

$$DGP = (5.87\ x\ 10^{-5})E_v + (9.18x\ 10^{-2})\ log\left(1 + \sum_i \frac{L_{s,i}^2 \omega_{s,i}}{E_v^{1.87} P_i^2}\right) + 0.16\ (3.1)$$



RESULTS: *Full-scale Testing Visual Comfort*

Daylight Glare Probability



RESULTS: *Full-scale Testing Energy Savings*

Lighting energy savings:

- 40% - 60%
- More variability for venetian blinds vs. roller shades
- Control strategies = similar savings
- Lower for overcast days vs. sunny/cloudy days

HVAC energy savings:

- 20% - 30%
- higher total energy savings compared to lighting

Visual Comfort:

- Significant improvement in visual comfort
- Challenges with direct sunlight vs. distraction

Thermal Comfort:

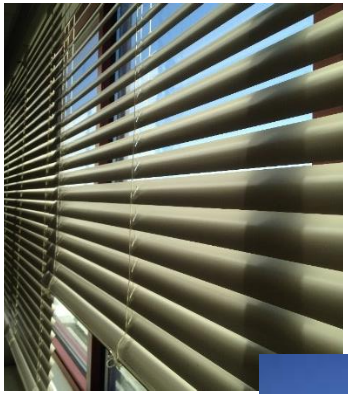
- Maintained throughout testing

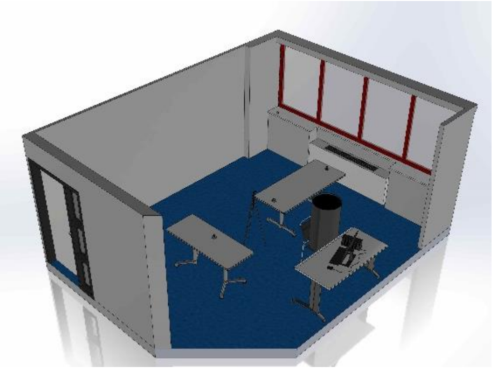
METHODOLOGY:

Control Strategy & Automation Development

Full-Scale Testing and Data Collection

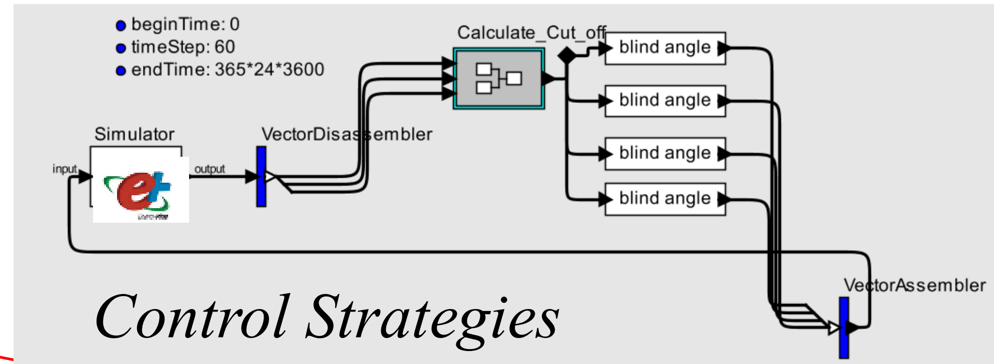
Calibrated Building Energy & Daylighting Simulation





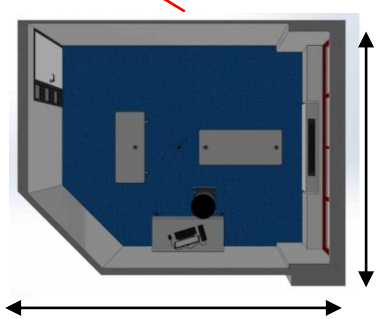
Calibrated Simulation: *Simulation Tools*

Simulation: *EnergyPlus v8.5 + DIVA for Rhino*



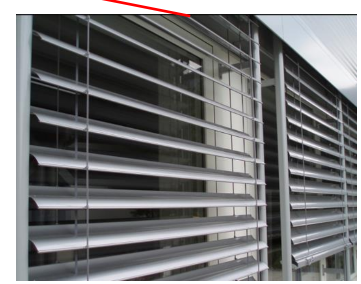
Physics Based Model

Weather data



Geometry

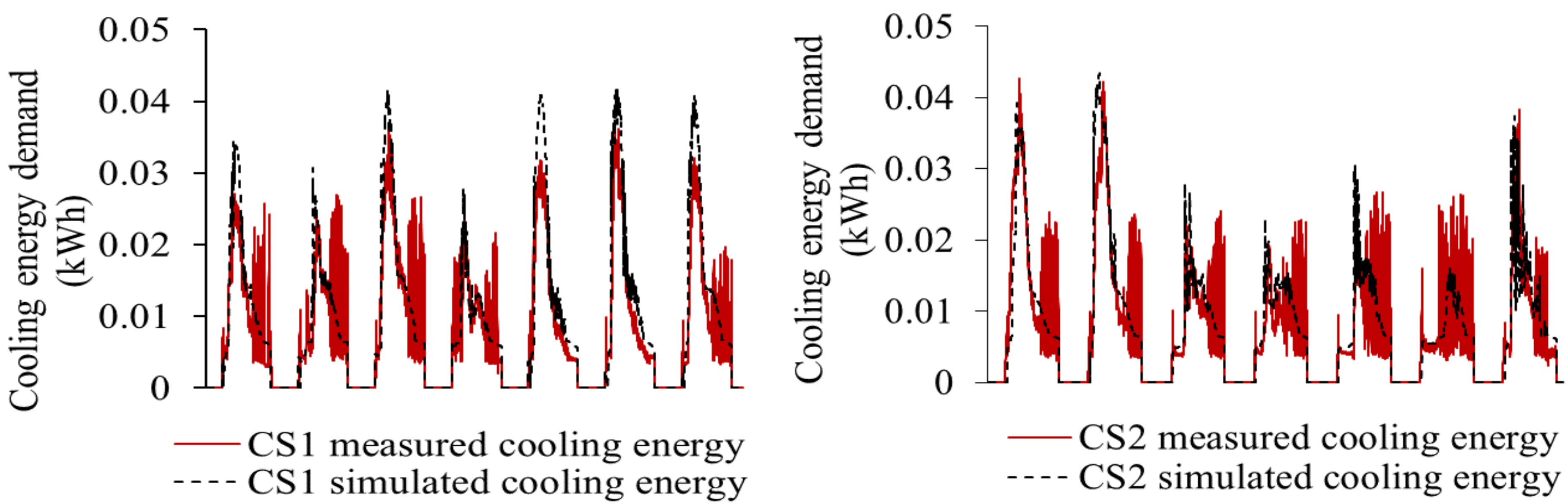
Internal Loads



Material Properties

Calibrated Simulation: *Control Strategy*

Comparison with Measured Data



<u>Cooling energy consumption</u> *CS1 (left) and CS2 (right)*

Calibrated Simulation: *Error*

Calibration error for data between 10 am to 6 pm

Case	**MBE (Overall energy)**	**CV of RMSE (Overall energy)**
Baseline	-6.2 %	17.7 %
Control Strategy 1	-6.9 %	22.6 %
Control Strategy 2	-10.4 %	19.2 %

Errors were within the range specified by ***ASHRAE Guideline 14***

MBE of 10% and CV of RMSE of 30% for hourly comparison

RESULTS: Annual Simulation

		Energy Consumption (kWh)		Energy Saving (kWh)		Energy Saving Percentage (%)	
		Des Moines	Tampa	Des Moines	Tampa	Des Moines	Tampa
Heating	Baseline	573	44				
	CS1	656	48	-82	-4.07	-14 %	- 9 %
	CS2	663	48	-89	-8.42	-16 %	- 8 %
Cooling	Baseline	3040	4746				
	CS1	2437	3986	602	760	20 %	16 %
	CS2	2382	3927	657	819	22 %	17 %
Lighting	Baseline	2087	2087				
	CS1	1148	1137	939	949	45 %	46 %
	CS2	1098	1070	988	1017	47 %	49 %
Total	Baseline	5702	6879				
	CS1	4242	5172	1459	1706	26 %	25 %
	CS2	4145	5046	1556	1832	27 %	27 %

CONCLUSIONS: *Testing and Simulation*

This can be improved using better dimmable lighting

Lighting energy savings:

- **Full-Scale Testing:** 40% - 60%
- **Calibrated Annual Simulation:** 46% - 49%

More for less efficient windows

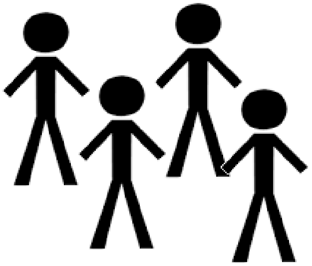
HVAC energy savings:

- **Full-Scale Testing**: 20% - 30% (cooling)
- **Calibrated Annual Simulation**: 16% - 17% savings (cooling)

Overall :

- 25-27% annual savings ***while maintaining comfort***
- Dynamic shading is more beneficial for buildings with less efficient windows
- Benefits in both heating- and cooling- dominated climates

NEXT STEPS: *Dynamic Fenestrations*



Cost Effectiveness & Non-Energy Benefit Quantification

Modeling Needs & Ease of model integration

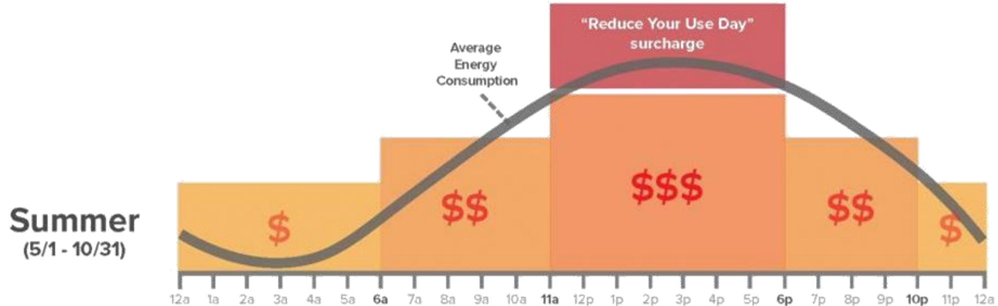
East and West Orientations

- Direct sunlight comfort evaluation/metric

Integration of occupant feedback

- Distraction of blinds operations vs. movement to optimize performance

Control strategies that integrate dynamic and TOU pricing to reduce energy demands and costs



Thank you

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