The potential of predictive modeling and automated building facade elements to attain thermal comfort

Troy Peters[1]
[1]Wentworth Institute of Technology, Boston, Massachusetts
[1]University of Massachusetts, Amherst, Massachusetts

ABSTRACT: Buildings are the largest contributor to climate change. Energy use and the release of carbon green house gasses by buildings are driving climate change while at the same time weather extremes are driving more energy use in buildings. Designing buildings that use less energy and possibly no energy for heating and cooling can break this feedback loop.

Passive solar design utilizing energy directly from climate and weather patterns and high mass for heating and cooling has been studied extensively. However, the problems with passive solar heating and night ventilation of mass is that human thermal comfort is not always achieved due to over heating in both heating and cooling modes, large indoor diurnal temperature swings, and the unpredictable nature of the weather from day to day and year to year. Climate change will only exacerbate the problem because the climate that a passive building was designed for might change and the anticipated weather extremes may fluctuate in ways the designer could not expect.

Predictive modeling is a method used to predict future performance and foresee the significances of change. It can be used in a building to modify the present characteristics of the building to increase the future performance of thermal comfort. The characteristics in a passive solar building that can most easily be changed are the use of operable night insulation on windows, ventilation rate and solar gain by use of operable shading. Weather forecasting and solar radiation forecasting has been modeled but is it accurate enough for building simulation modeling?

This paper explores the potential of using predictive modeling and the automation of facade elements to achieve thermal comfort in buildings, and in particular the use of weather forecasts to help a passive solar building use the usual high thermal lag time to its advantage. These are investigated through a review of the literature on predictive modeling and an energy simulation on a simple single zone room that is heated by direct gain passive solar. The simulation results show that predictive modeling has potential to keep a passive solar building in the thermal comfort zone on consecutive days of low solar radiation.

KEYWORDS: Predictive Modeling, Thermal Comfort, Passive Survivability, Passive Solar Building

1.0 INTRODUCTION AND BACKGROUND

Climate change along with corresponding weather extremes are creating new and pressing problems for the built environment. Buildings are the largest contributor to climate change using 39 percent of U.S. primary energy consumption (21 percent residential and 18 percent commercial in 2006). Heating and cooling of buildings accounted for 39 percent of residential total energy end use and commercial buildings 32 percent. It can be calculated that heating and cooling of buildings accounted for 14 percent of the total U.S. primary energy consumption. Energy use and the release of carbon green house gasses by buildings are driving climate change while at the same time weather extremes are driving more energy use in buildings. Designing buildings that use less energy and possibly no energy for heating and cooling can break this feedback loop. Net zero energy buildings that produce the same amount of energy as they use, still have a net gain in released green house gasses as they can supply and draw energy from the grid that may use energy produced by fossil fuels.

1.1. Passive solar design

Passive solar design utilizing energy directly from climate and weather patterns and high mass for heating and cooling has been studied extensively peaking in the late 1970's. Heating and cooling energy use in passive buildings has been reduced by the manipulating of: window orientation, size, type and the use of operable night insulation; insulation level of walls, roof and floor; mass type, area and thickness or the use of phase change materials; ventilation rate, natural, mechanical and heat recovery; and horizontal and vertical shading device both fixed and operable.

The problems with passive solar heating and night ventilation of mass is human thermal comfort is not always achieved due to over heating in both heating and cooling modes, large indoor diurnal temperature swings, and the unpredictable nature of the weather from day to day and year to year. Climate change will only exacerbate the problem because the climate that a passive building was designed, might change and the anticipated weather extremes may fluctuate in ways the designer could not expect.

Over heating and temperature swings are minimized in passive solar buildings by the use of thermal mass whose characteristics, material, exposed area and thickness, are tied as a ratio to the characteristics of the equator facing window, area and type. As a rule, the larger the area of equator facing glazing, the greater the area of thermal mass. Large window areas lead to large areas of mass, usually a ratio between three and nine mass area to window area. Thermal mass will temper and phase-shift the effects of solar radiation, indoor and outdoor temperature and ventilation in a building. The time-shifting effect of thermal mass may also contribute to thermal discomfort if the mass is too warm when cooling is desired or too cold when heating is desired.

1.2. Predictive modeling

Predictive modeling is a method used to predict future performance and foresee the significances of change. It can be used in a building to modify the present characteristics of the building to increase the future performance of thermal comfort. The characteristics in a passive solar building that can most easily be changed are the use of operable night insulation on windows, ventilation rate and solar gain by use of operable shading.

Some of the questions that this paper addresses are:

- Can predictive control improve the energy performance and thermal comfort in a passively heated and cooled building using only façade elements?
- Which building elements are the most effective in providing thermal comfort in a predictive control system?
- Is weather forecasting and solar radiation forecasting accurate enough for building simulation modeling?

These questions are investigated through a review of the literature on predictive modeling and an energy simulation on a simple single zone building that is heated by direct gain passive solar. The simulation first optimizes the zone through iterative parametric changes. The simulation then looks at keeping the operative temperature of the zone in the PMV comfort range for a two-day period of low direct solar radiation using predictive modeling.

1.3. Literature Review of Predictive Modeling

Predictive control and predictive modeling studies have mostly been done on buildings that rely on mechanical heating and cooling systems but the studies contain lessons for passive system design. The studies have used stimulation, test rooms and real buildings. Predictive control showed good results in the high mass building with radiant heating in a full scale outdoor test room. The floor heating system control by generalized predictive model was then evaluated through computer simulations (Chen 2002).

Model predictive control generally provides superior performance to conventional HVAC controllers. The accuracy of the model and weather forecasting affect the performance of MPC. Weather forecasts should be updated frequently to improve controller performance. Simple MPC systems outperformed the conventional control systems that do not use any predictive algorithms. Thermal storage can be used for peak shifting and MPC with thermal storage will outperform systems without thermal storage. Buildings with little thermal mass can use water storage to improve the performance of the building. (Afram, 2014)

Another study looked at the control of the heavyweight radiant slab system in a typical office building during the summer season in a dry and hot climate. (Feng, 2015) The chiller was eliminated and the only cooling source is a cooling tower. The MPC controller was able to maintain zone operative temperatures at the thermal comfort level more than 95 percent of the occupied hours for all zones. Compared to a typical HVAC controller, MPC reduced the cooling tower energy consumption by 55 percent and pumping power consumption by 25 percent.

A study looked at the value of forecasting weather variable inputs and energy optimization algorithms for commercial building energy systems. It was found that weather variables are a significant component of building energy systems and minimizing the uncertainty in weather predict can lead to energy reductions of 15–30 percent compared to a deterministic and non-weather sensitive controls. (Lazos, 2014) Another study also shows that the quality of the predicted weather data is important to guarantee reliable results (Oldewurtel, 2012)

Another paper (Petersen, 2014) looked at the effects of weather forecast uncertainty on energy use and indoor climate of a building that uses a model predictive control. The effects are quantified by comparing the simulation with differences in forecasted and actual weather data. The effects were identified through a differential sensitivity analysis of four building design parameters: orientation, thermal mass, solar shading and window area. The analysis was performed using Danish weather data from two different years. The results from the simulation study showed a potential for energy savings and improvements in thermal indoor environment despite the uncertainty in the weather forecasts. Buildings with heavy thermal mass were less dependent on the accuracy of the weather forecasts compared to buildings with very light thermal mass. The performances of the light thermal mass buildings were especially sensitive to the precision of solar irradiance forecasts.

A simple summary of the literature review is that high mass buildings perform better than low mass buildings in modeled predictive control and accurate weather forecasts make the predictions more accurate but high mass buildings are less sensitive to forecast inaccuracies than low mass buildings.

2.0 SIMULATION

2.1. Simulation procedure

A simple direct gain passive solar building (Fig. 1) with two occupants was modeled in Energyplus 8.2 for one full year in Boston, Massachusetts. The zone had dimensions of 4 meters by 7 meters by 3 meters high. The only window was on the south façade and the size of the window was held constant at 70 percent of window to wall ratio. A south facing shading device can be varied in size. The floor was an insulated concrete slab of variable thickness and the interior walls and ceiling was covered with gypsum. The insulation level of the walls, ceiling and slab were varied. Ventilation was achieved by an air to air heat exchanger.

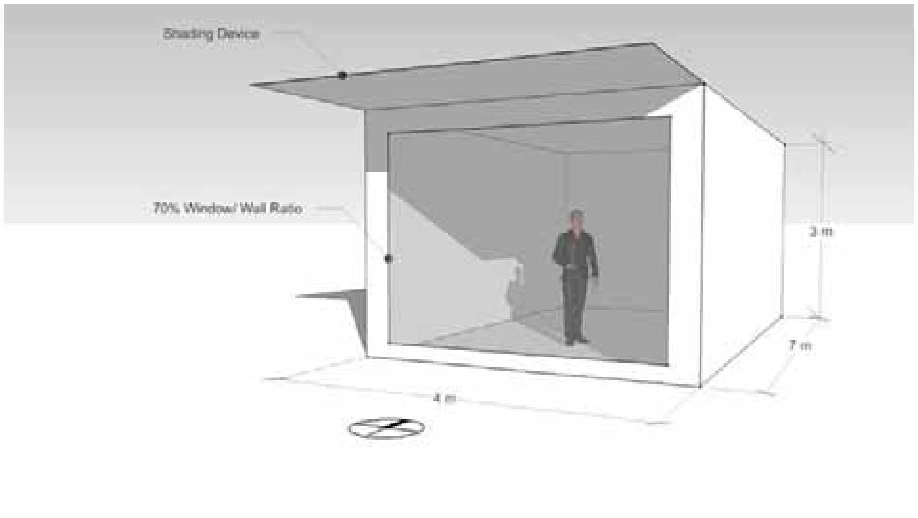

Figure 1: Simple direct gain model simulated.

Five building parameters were changed (Table 1) to see their effect on the indoor comfort level. First, the building insulation level of the walls, ceilings and floor was changed from a conductance of (0.5, 0.25, 0.17, 0.13, 0.10, 0.08) W/m^2. The zone operative temperature for each conductance was plotted and compared. Holding the conductance at 0.08 w/m^2, the south facing window type was changed from double clear argon to triple clear argon to quadruple clear argon. The zone operative temperature from each window type was plotted and compared. Next the concrete floor thickness was increased from 0.05 m to .25 m in 0.05 m increments. The zone operative temperature was compared and the floor thickness was then held at 0.15 m thick. Two formulations of a phase change material were placed in the ceiling of the building. Both have a heat capacity of 575 $Wxhr/m^2$ and a melting point of 27° C and 21° C. These results were plotted. The floor thickness was then held at 0.15 m thick and the phase change material was removed. The shading device was added and increased in length from 0.5 to 2.5 m in 0.5 m increments. The zone operative temperature was plotted and the shading device was held at 1.5 m length and then the ventilation was changed from (0.6, 1.25, 1.75, 2.50, 3.0) air changes per hour. Ventilation was achieved using an air-to-air heat exchanger with 80 percent efficiency. These results were plotted.

Table 1: Simulation parameters

Boston, MA	
EPW-TMY3	
Latitude	42.37
Longitude	-71.02
NS length (m)	7
EW length (m)	4
Height (m)	3
South Window/Wall	70%
Occupants	2

	SIMULATION NUMBER																											
	1	2	3	4	5	6	7	8	9	10	10a	10b	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Insulation Level																												
0.50 W/m2-k	x																											
0.25 W/m2-k		x																										
0.17 W/m2-k			x																									
0.13 W/m2-k				x																								
0.10 W/m2-k					x																							
0.08 W/m2-k						x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Window Type (SHGC, U)																												
Double Clear Argon (0.76, 2.56)	x	x	x	x	x	x																						
Triple Clear Argon (0.69, 1.62)							x																					
Quadruple Clear Argon (0.62, 1.20)								x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Concrete Floor Thickness																												
0.05 m	x	x	x	x	x	x	x	x																				
0.10 m									x																			
0.15 m										x	x	x			x	x	x	x	x	x	x	x	x	x	x	x	x	x
0.20 m													x															
0.25 m														x														
Ceiling PCM																												
Melting 27, Capacity 182											x																	
Melting 21, Capacity 182												x																
Shading Device Length																												
None	x	x	x	x	x	x	x	x	x	x	x	x	x	x														
0.50 m															x													
1.00 m																x												
1.50 m																	x			x	x	x	x	x	x	x	x	x
2.00 m																		x										
2.50 m																			x									
Ventilation Rate (ACH)*																												
Constant=0.60																				x								
Constant=1.25																					x							
Constant=1.75	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x									
Constant=2.50																						x						
Constant=3.00																							x					
Predicted Ventilation Rate (ACH)*																												
Before Prediction=1.75																								x	x	x	x	x
After Prediction=0.60																								x				
After Prediction=1.25																									x			
After Prediction=1.75																										x		
After Prediction=2.50																											x	
After Prediction=3.00																												x

* With 80% efficient Heat Exchanger

2.2. Simulation results

The results of the simulation were plotted (Fig. 2) showing the zone operative temperature for a four-day period from February 18th to February 21st. These four days were chosen because the direct solar radiation was high on the 18th, followed by two days of very low direct solar radiation and then the 21st has high direct solar radiation in the EPW weather file that was used for the simulation. The comfort zone is plotted using ASHRAE 55, PMV method for operative temperature and a maximum predicted mean vote of 10 percent. The low comfort limit of 18.5 °C uses a CLO value of 1.49 and a MET of 1.0. The high limit of 27.4 °C uses a CLO value of 0.5. The results show that all of the simulations were within the comfort zone for some time period during the four-day span. The simulations with high mass were in the comfort zone for the most amount of time during the four-day time period. The single plot was broken up into four individual plots to clarify the effect of changing each of the parameters.

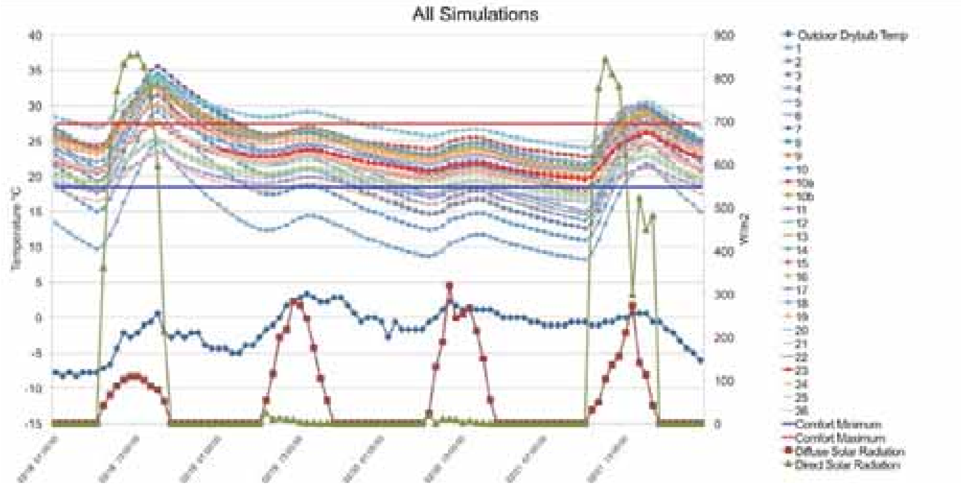

Figure 2: Zone operative temperature, outdoor temperature and radiation for all simulation runs over four day period.

Changing the insulation level and glazing type (Fig. 3) did not produce remarkable results, lower conduction at the envelope had higher zone operative temperatures, except for the change from triple clear argon glazing to quadruple clear argon glazing. This change had nearly the same zone operative temperature however the quadruple clear argon glazing had a lower maximum zone operative temperature and a higher minimum zone operative temperature than the triple clear argon glazing.

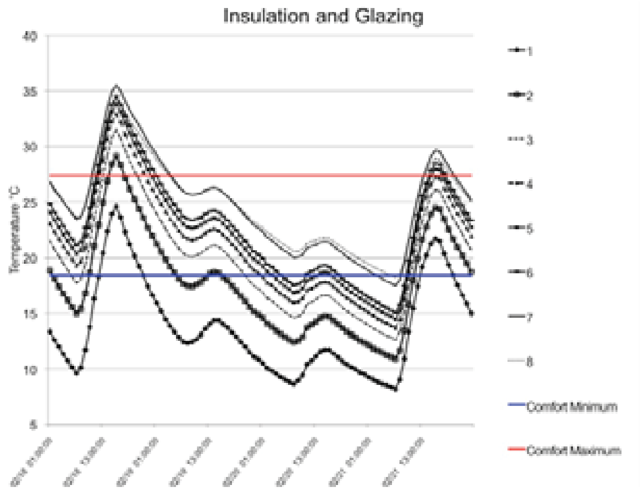

Figure 3: Zone operative temperature for changes in insulation and glazing over four-day period.

The mass and phase change materials results (Fig. 4) show the zone operative temperature swing, both daily and weekly, decreased as the thickness of the slab increased, as expected. When phase change material is added to the ceiling the formula with a melting point of 27° C has the best result since the phase change material with a melting point of 23° C would remain liquid over the four day period so it has little effect on the zone operative temperature. Shading (Fig. 5) and ventilation changes also performed as expected.

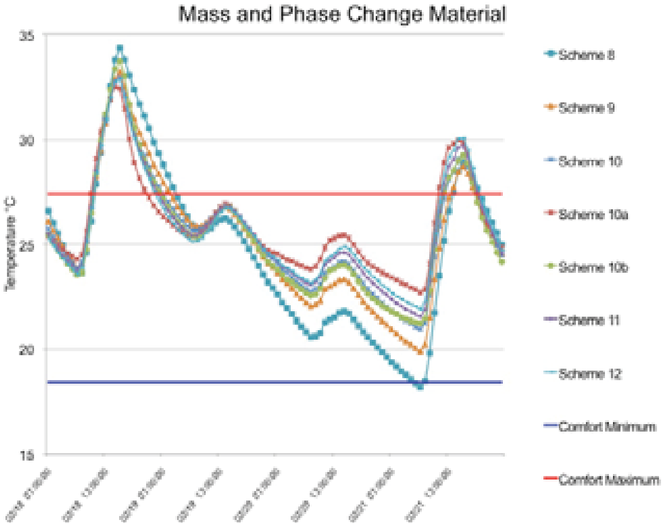

Figure 4: Zone operative temperature for changes in mass and phase change material over four-day period.

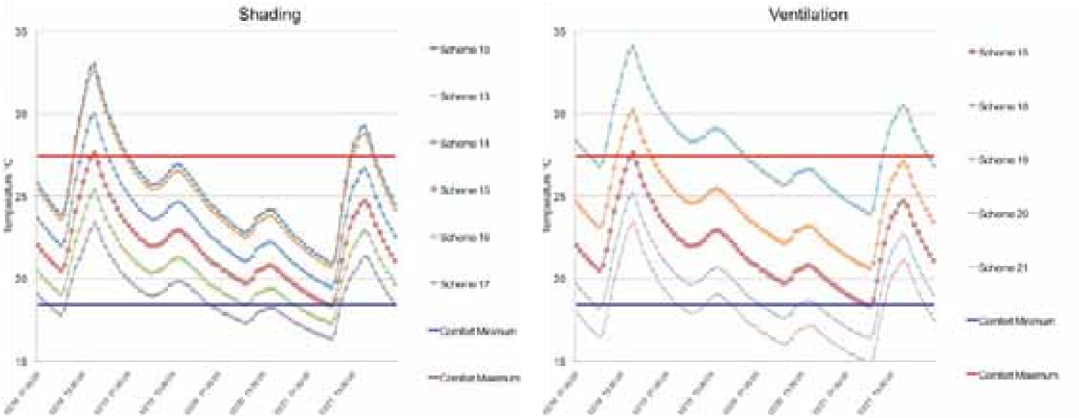

Figure 5: Zone operative temperature for changes in shading and ventilation over four-day period.

2.3. Predictive modeling simulation test

The simulation results show that changing the parameters will change the zone operative temperature in scale and in profile. The parameters that are the easiest to change are shading and ventilation. A simple test for predictive modeling is performed by changing the ventilation rate for the direct gain passive solar building for a period of two consecutive days of low solar radiation during the heating season. A weather file in the EPW format was analyzed and two consecutive days of low direct solar radiation were found on February 19th and February 20th. The advantage of a weather file compared to real weather is the fact that the proceeding days weather is known in a weather file while real weather forecasts must be predicted. Knowing that the direct solar radiation would be low for two consecutive days, the ventilation rate was changed in the simulation by five different rates (Fig. 6) to observe possible zone operative temperatures. Scheme 22 gave the best results for comfort. In a building controlled by predictive modeling, the ventilation rate could be changed at midnight on the evening before the start of the two consecutive days of low direct solar radiation and the building would remain comfortable. In a building controlled by a thermostat, the ventilation would probably not be changed, scheme 24 has a constant ventilation rate, until it fell to the lower end of the comfort zone and might need supplemental heating to bring the zone back into the comfort zone.

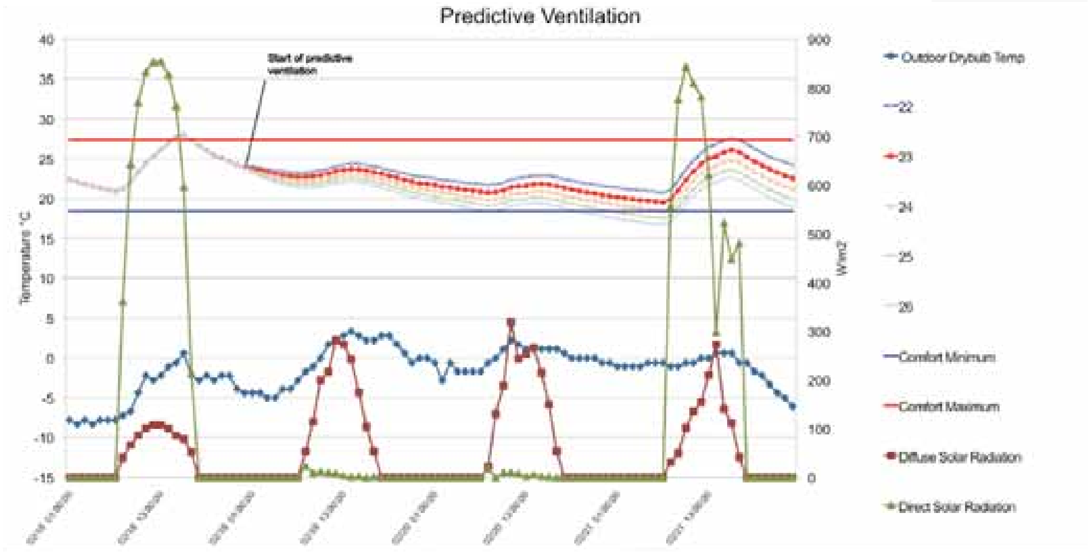

Figure 6: Zone operative temperature for predictive ventilation over four-day period.

CONCLUSION

The results of the initial simulation are encouraging but more study is needed. The next steps will be to simulate predictive control over a whole year for thermal comfort and to develop rules for controlling ventilation and shading based upon predicted weather. The potential of predictive modeling and automated building facade elements to attain thermal comfort does look promising.

REFERENCES

Afram, Abdul, and Farrokh Janabi-Sharifi. 2014. “Theory and Applications of HVAC Control Systems – A Review of Model Predictive Control (MPC).” *Building and Environment* 72 (February): 343–55.

Chen, T. Y. 2002. “Application of Adaptive Predictive Control to a Floor Heating System with a Large Thermal Lag.” *Energy and Buildings* 34: 45–51.

Feng, Jingjuan (Dove), Frank Chuang, Francesco Borrelli, and Fred Bauman. 2015. “Model Predictive Control of Radiant Slab Systems with Evaporative Cooling Sources.” *Energy and Buildings* 87 (January). Elsevier B.V. 199–210.

Lazos, Dimitris, Alistair B. Sproul, and Merlinde Kay. 2014. “Optimisation of Energy Management in Commercial Buildings with Weather Forecasting Inputs: A Review.” *Renewable and Sustainable Energy Reviews* 39 (November): 587–603.

Oldewurtel, Frauke, Alessandra Parisio, Colin N. Jones, Dimitrios Gyalistras, Markus Gwerder, Vanessa Stauch, Beat Lehmann, and Manfred Morari. 2012. “Use of Model Predictive Control and Weather Forecasts for Energy Efficient Building Climate Control.” *Energy and Buildings* 45 (February): 15–27.

Petersen, Steffen, and Katrine Wieck Bundgaard. 2014. “The Effect of Weather Forecast Uncertainty on a Predictive Control Concept for Building Systems Operation.” *Applied Energy* 116 (March): 311–21.