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A METHOD OF ENERGY SIMULATION FOR DYNAMIC BUILDING ENVELOPES

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ABSTRACT

Some emerging smart materials, like the variable-conductance vacuum insulation by changing hydrogen gas pressure, thermal adaptive coatings made by electronic fibers, and various sandwiched wall with controllable thermal properties, all present a rapid development in the material field related to dynamic building envelopes. As the envelope materials and construction processes move toward the smarter and more adaptive, it becomes more and more necessary to properly understand the potential energy performance made available through dynamic envelopes, especially on the whole-building energy scale. However, the challenge is that most current energy simulation methods with static (or a limited range) material settings are hard to fully support the energy analysis of these dynamic building envelopes. This research explored a parametric simulation method using the Energy Management System (EMS) module of *EnergyPlus* to meet the energy simulation needs of dynamic building envelopes. This method is discussed in this paper and also appears to producing expected results through a comparative energy analysis of an office model.

INTRODUCTION

As interest increases in the area of net zero energy buildings, some studies are focusing on variable envelope components which may greatly impact on indoor environmental performance and building energy usage. These dynamic properties include – but are not limited to – phase-change materials and thermo- or electro-chromatic glazing. Several smart materials such as Smart Insulation (Knotts et al., 2011), Active Thermal Walls based on thermoelectricity (Khire et al., 2005; Xu et al., 2007), and other various sandwiched walls with controllable thermal properties (e.g., Di Giuseppe et al., 2015; Elsarrag et al., 2012) have been presented at the experimental stage and on a materials scale. Consider, for instance, smart insulation that utilizes bimetallic switch-type thermally-expansive materials that can change their contact area or air gap space in order to increase or decrease conductive heat transfer. Such materials can achieve a range from R-5 to R-35 on their wall insulation (Knotts et al., 2011). These experimental construction processes and materials are controlled by users who modulate their thermal and/or optical properties in response to real-world boundary conditions.

Because of the development trend of dynamic building envelopes, it has become necessary to have an energy simulation method to analyze the potential energy savings of dynamic envelopes, especially at the whole building scale. The energy simulation of dynamic envelopes is also useful to select or design appropriate dynamic properties and control parameters since this is a trade-off between the complexity or cost on smart materials and energy saving performance of the smart materials. However, most simulations of building envelope construction suffer from predictable restrictions related to constant and static properties. For example, EnergyPlus incorporated a conduction finite difference (CondFD) solution algorithm that simulates phase change materials, movable insulation, and thermochromic glazing. EnergyPlus offers certain built-in options that allow users to conduct the dynamic properties of the building envelopes. However, the controls for these built-in functions are limited to responding to specific materials and applications, and are not able to set up experimental parametric equations such as correlations to solar radiation absorption. For example, "Material Property: Phase Change" specifically describes the temperature-dependent material's thermal heat capacity properties. "Surface Control: Movable Insulation" is useful when employing an extra amount of movable insulation on either the inside or outside layer of a construction. The control scheme is limited to the setup in EnergyPlus's schedule. Our study was proposed to meet the potential energy analysis needs of design engineers working on emerging dynamic or smart building materials for envelopes. So, a more controllable and programmable energy simulation approach compared with the aforementioned built-in functions should be studied.

The Energy Management System (EMS) module has been added to the *EnergyPlus* whole-building energy simulation program since the version 4.0. It uses the *EnergyPlus* Runtime Language (Erl), a simplified programming language, to set up the advanced control algorithms and scenarios for the *EnergyPlus* models. The EMS controls and the flexibility of the Erl program allow design engineering who are working on some novel control strategies about building systems and construction that are not possible with standard *EnergyPlus* control objects for a true whole-building simulation (Ellis et al. 2008). Also, as the development of *EnergyPlus*, the EMS actuators are evolved to control more variables, such as outdoor air conditions, surface construction and outside boundary conditions in recent version updates.

The aim of this study is therefore to explore a parametric simulation method based on the *EnergyPlus* platform and its EMS module to evaluate the energy performance of ideal, adaptive, and dynamic building envelopes. Furthermore, in order to verify the application of this method, we also conducted a series of comparative energy analysis in relation to the reference models with conventional and static building envelopes. A series of hypothesized dynamic envelope properties depent upon external and internal environmental conditions were proposed and then parametrically modelled through the EMS module in *EnergyPlus*.

MODELING AND SIMULATION

Dynamic building envelopes have different properties responding to the other stimuli which are normally considered as independent variables. On the counterpoint, envelope behaviors (e.g. insulation changes, transmittance changes, etc.) are deemed as dependent variables. Based on the worldwide emerging studies on dynamic envelope materials and construction, we hypothesized four dynamic properties of building envelopes: R-values of opaque components (walls and roofs, separately), U-factors of windows, and Solar Heat Gains Coefficient (SHGC) of windows. The challenge, as mentioned in the first section, was to conduct complex controls and modeling routines for how we want the dynamic building envelopes to behave. The EMS is an advanced application for users who need to write *EnergyPlus* Runtime Language (Erl) for the high-level and supervisory control to override selected aspects of *EnergyPlus* modeling. The essential steps of using the EMS are related to three elements: EMS sensors, EMS actuators, and EMS calling points. The simulation framework is shown in Figure 1.

- EMS sensors: The input object "Energy Management System – Sensor" uses the normal *EnergyPlus* output variables, which can be obtained by looking at the RDD file generated by similar models with the same types of components and systems (DOE, 2015). This command was used in our simulation study to set up the independent variables. After our search and study on the RDD file, we selected "Site Outdoor Air Dry Bulb Temperature", "Surface Outside Face Incident Solar Radiation Rate Per Area", and "Zone/Sys Sensible Cooling Rate" as the input objects of the EMS sensors. The last, "Zone/Sys Sensible Cooling Rate," was used to determine the pre-time step Heating, Ventilating, and Air Conditioning (HVAC) status.
- EMS actuators: EMS actuators are used to select features or components of *EnergyPlus* models and override them according to a series of new settings. The *EnergyPlus* EMS developers added built-in actuators such as HVAC systems, thermal envelopes, internal gains, air movement, etc. (DOE, 2013). By using these actuators, we were also able to set up the parametric correlations of the independent (sensors) and dependent variables (actuators).
- EMS calling points: This command allows users to confirm when and where Erl programs will be initiated to control the envelope properties. In this simulation analysis, we used "Begin Time Step Before Predictor" in the EMS calling manger. This causes the energy prediction and calculation of each time step to be processed after overriding the new variables associated with the envelope materials.

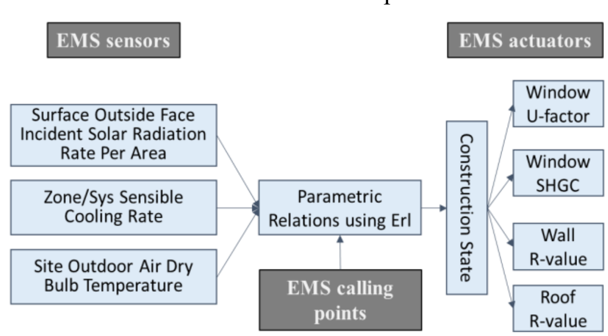

Figure 1. Framework of the parametric modeling and simulation using the EMS in EnergyPlus

Modeling of opaque assemblies

Controlling the envelope insulation in *EnergyPlus* means adjusting the surface construction; this is referred to as the "Construction State" on the "Surface" EMS actuator and was also used to control the windows' dynamic properties. The EMS Construction Index Variable input object was used to assign new insulation variables from the Erl parametric correlations.

In our hypothesis, the insulation of the walls and roofs were set at the low thermal conductivity (higher R-values) when the outside air temperature was too high or too low but at the high thermal conductivity (lower R-values) when outside air temperature was falling into the mild temperature zone. In this assumption, therefore, walls and roofs ideally enable indoor heat gains to be transferred to outside during the summer cooling period, and they maintain the indoor temperature during the winter heating period. This was a simple piece-wise linear relationship was between the outside temperature of the material surface and thermal conductivity of this insulation material. One setting example in this project case study is shown in Figure 2. Built upon this, the overall R-value could be ranged from 17 to 50. In the practical perspective, this variable insulation may be not achievable at this time. However, some literature has shown the potential variable insulating ability. For instance, the smart insulation device at the laboratory stage has achieved a range of 5 to 35 R-values using fin-paneled walls (Knotts et al. 2011).

In this case study using the EMS to model the opaque assemblies, the changing boundaries (external temperature values) were just proposed in this simulation method validation study and without further optimization. In addition, more complex temperature dependent insulation than the piece-wise linear relationship used in this work can be setup in the EMS.

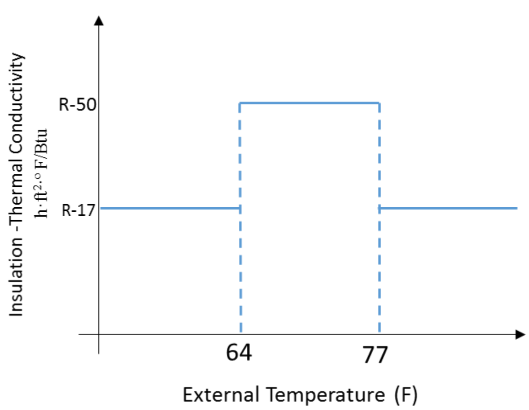

Figure 2. Example of the insulation change within the external temperature boundaries

Modeling of dynamic windows

In this study, we expected to go beyond the basic electrochromatic glazing function and explore more controllable dynamic window modeling methods. The range of overall windows' U-factors was assumed at 0.1Btu/h•ft²•°F - 0.5Btu/h•ft²•°F, and the range of SHGC was assumed at 0.10-0.35. The hypothesized control scheme of the window properties was designed to utilize the outside solar radiation by overriding any high SHGC values and reduce heat loss by overriding any low U-factors during heating conditions. The low SHGC values and U-factors were set up during cooling conditions. Similar to the wall and roof insulation settings, the high U-factors were only utilized during appropriate outside air temperatures to facilitate heat transfer. In the real world, this control scheme has yet to be developed but some studies or experiments, such as PCM-filled glass panes (Zhong et al., 2015) and adaptive heat transfer window shading devices (De Bruin, 2014), have shown promising preliminary results in which both window U-factor and SHGC can be controlled.

Figure 3 shows an example of the change of overall U-factor and SHGC based on the external temperature in this case study. In addition to the external air temperature, "Surface Outside Face Incident Solar Radiation Rate Per Area" (sense outside solar radiation is higher than 100 W/m^2) and "Zone/Sys Sensible Cooling Rate" (sense the pre-time-step HVAC status - cooling or heating status) were also used as the independent variables using the Erl program.

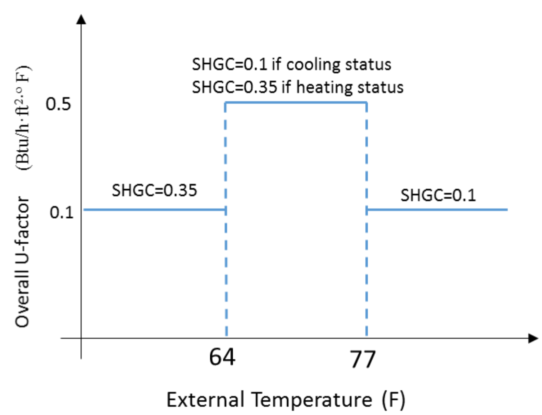

Figure 3. Example of SHGC and U-factor change within the external temperature boundaries

In the built-in EMS actuators, similar to the modeling of opaque assemblies' dynamic insulation, "Surface" and its "Construction State" option were used to control the input objects "SHGC" and "thermal conductivity" under the *EnergyPlus* "Fenestration Detailed" section.

Reference models

To verify that this parametric simulation method is workable to perform energy analysis of dynamic building envelopes, we also conducted several comparisons between our hypothesized dynamic building envelopes and reference models with conventional static building envelopes. We adopted a small office prototype model with one floor 5,500 ft^2 developed by the Pacific Northwest National Laboratory (PNNL), which complies with the ASHRAE Standard 90.1-2013. The reference model's information and envelope properties are shown in Table 1.

As shown in Table 1, four different climate zones and representative cities -- Houston, TX (Climatic zone number 2A), San Francisco, CA (Climatic zone number 3C), Baltimore, MD (Climatic zone number 4B), and Chicago, IL (Climatic zone number 5A) -- were selected for this simulation experiment.

DISCUSSION AND RESULT ANALYSIS

This study used and verified the EMS actuator "Surface" and its control variable "Construction State" to model dynamic properties related to the insulation of walls and roofs, SHGC and the overall U-factor of windows. This method can also be useful for modelling other dynamic technologies used in building envelopes. However, there are some issues that must be resolved. Firstly, the "Construction State" EMS actuator cannot work under the following two *EnergyPlus* heat transfer algorithms: "Conduction Finite Difference Simplified" and "Combined Heat And Moisture Finite Element." Secondly, it is risky to use the surface construction state actuator to generate incorrect simulation results if the thermal properties have radical changes. A data system called "thermal history" has evolved during the simulation process for envelope construction in *EnergyPlus*; it can be reused for new constructions generated from the Erl parametric settings. If the construction state has radical changes, the thermal history data may conflict with the new construction state; this will result in errors or warnings to stop the simulation. Therefore, in order to proceed with the new construction assignment, the dynamic properties of the envelopes should retain the same structures and features. For example, the number of finite difference nodes in the original construction should be kept the same for the new construction.

In addition, the energy-related results produced by our proposed dynamic envelopes were compared with the other three reference models in order to verify whether the dynamic envelope behaviors were successfully modelled and simulated using this simulation method. Table 2 shows the HVAC energy use levels of our four models. It can be seen that the dynamic envelopes produced averagely ~23.9 MMBtu (or ~46.2%) savings, and ~19.3 MMBtu (or ~38.2%) savings on the annual cooling and heating loads in the four cities, relative to the Basic Models and the Advanced Models respectively. Because of the envelope behaviour under different environmental conditions, even compared to the Ultra Models which have the highly-insulated but static envelope properties, the dynamic building envelopes were still able to achieve averagely ~9.3 MMBtu (or ~18.2%) savings in the four cities. These energy saving results, therefore, demonstrated that the dynamic envelope behaviors followed our programs and parameter settings in the EMS.

Finally, in order to verify that this simulation method would work for different envelope assemblies, we also explored the performances of each assembly of the dynamic building envelopes, relative to each of the other three models and in all four cities. It was important to

Table 1. Reference model basic information

Total Floor Area (sq. ft.)	5500 (90.8 ft. x 60.5ft)			
Aspect Ratio	1.5			
Number of Floors	1			
Window Fraction (Window-to-Wall Ratio)	24.4% for South and 19.8% for the other three orientations (Window Dimensions: 9.0 ft. x 5.0 ft. punch windows for all façades)			
Floor to floor height (feet)	10			
Floor to ceiling height (feet)	10			
Glazing sill height (feet)	3 (top of the window is 8 ft. high with 5 ft. high glass)			
Climatic zone	2A	3C	4B	5A
Roof R-value	R-38	R-38	R-49	R-49
Wall R-value	R-13+R-3.8 c.i.	R-13+R-3.8 c.i.	R-13+R-7.5 c.i.	R-13+R-10 c.i.
Window U-factor	0.45	0.41	0.38	0.35
Window SHGC	0.25	0.25	0.26	0.26

highlight the contribution to energy savings made possible by single envelope components with dynamic properties, in order to facilitate a better understanding of which parts of the building envelope should be considered worthy of being made dynamic, respective to specific building information and climatic conditions. The simulation results for each of the separated components (Roofs Only, Walls Only, Roofs and Walls, and Windows Only) were obtained for this study. Because the savings illustrated in the four models examining each envelope assembly were based on the same baseline climate conditions, we were able to compare the contributions of each assembly with regards to savings in the heating and cooling loads. As expected, compared to other reference models, dynamic windows consistently played a more significant role in heating and cooling load savings.

Table 2. HVAC energy use in the four different models

	Houston		San Francisco		Baltimore		Chicago	
	MMBtu	GJ	MMBtu	GJ	MMBtu	GJ	MMBtu	GJ
Baseline Models	55.91	58.97	31.18	32.88	56.19	59.26	64.54	68.07
Advanced Models	50.17	52.91	30.43	32.09	51.29	54.09	57.63	60.77
Ultra Models	37.74	39.81	22.89	24.14	39.35	41.49	49.7	52.41
Dynamic Models	29.5	31.12	16.47	17.37	29.42	31.02	37.05	39.08

CONCLUSION

In this research, we explored the parametric modelling and simulation method to evaluate energy performance of dynamic building envelopes. In general, the *EnergyPlus* EMS module's use of a simple programming language to define control scenarios provides a workable method for testing dynamic building envelopes during the design and experimental stages, before such envelopes need to be tested and implemented in real-world conditions. As more useful EMS actuators are developed, this parametric modelling and simulation method will enable even more novel dynamic building envelope design concepts and creations.

This method also produced reasonable energy results after a comparative analysis of the heating, cooling, and ventilating loads in the different envelope settings and the four selected climate conditions. The results presented in this research are from hypothesized dynamic envelope properties that are theoretically achievable. Although the appropriate materials and envelopes have yet to be developed, important knowledge can be drawn from this comparative study concerning the entirety of the building energy simulation approach for dynamic envelopes and the associated annual heating and cooling load savings potential.

The focus of future studies should be two-fold: to verify the proposed simulation method and energy savings by using real properties of dynamic building envelopes, and to research the energy performance produced by using dynamic envelopes in different building typologies and climatic conditions.

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