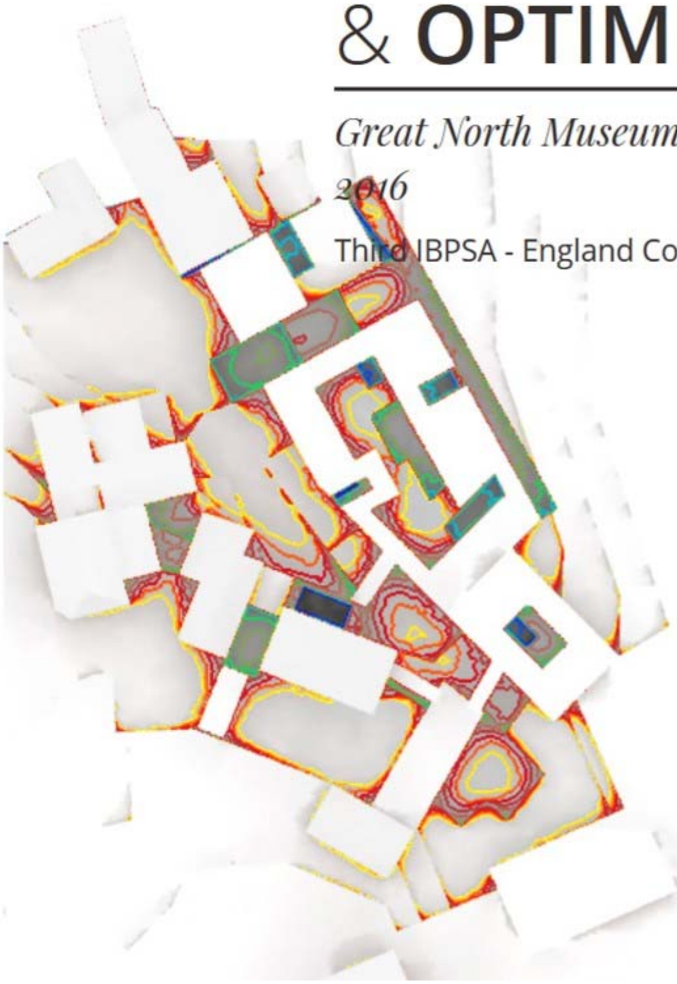

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ENERGY PERFORMANCE OF FUTURE DYNAMIC BUILDING ENVELOPES

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ABSTRACT

Innovative building envelopes have become more adaptive and interactive by responding to external climatic conditions and internal user comfort desires in ways that enhance energy performance and indoor comfort levels. Several emerging smart materials, such as variable-conductance vacuum insulation that operates by changing hydrogen gas pressure, thermal adaptive coatings made by electronic fibers, and various sandwiched walls with controllable thermal properties, all present a rapid development in the materials field and vast implementation potential in building envelopes. This research used a parametric simulation method that couples an optimization approach to access the potential energy savings of the dynamic building envelopes, as compared to the other three reference models in four cities representing four different climate zones. The findings indicate that the dynamic properties of the building envelopes significantly reduced the heating and cooling loads and peak demands of the buildings in the four cities.

INTRODUCTION

The thermophysical and optical properties of building envelopes are key factors defined by the materials and geometry of the building envelope components. As interest increases in net-zero energy buildings, even current high-performance envelopes can barely achieve their goals. Most available envelope designs work either where heating or cooling (but not both) is needed, due to the dominant climate. One way to improve building energy efficiency would be to develop dynamic building envelope systems being able to alter their thermal and optical properties according to seasonal/daily climatic variations. 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. These innovations may have a strong potential for implementation in building envelopes seeking better energy efficiency.

However, due to the complexity of dynamic envelope behavior and control parameters, it is important to access the energy savings at the design stage and on the whole-building energy. Our study adopted the Energy Management System (EMS) module of *EnergyPlus* to evaluate the energy performance of dynamic building envelopes. We selected a small office prototype model developed by the U.S. Department of Energy (DOE) as our case study. A series of theoretical dynamic envelope properties dependent upon ambient temperature, solar radiation, and indoor Heating, Ventilating, and Air Conditioning (HVAC) system status were proposed and parametrically modelled through the EMS module. Then, we conducted comparative energy analyses in relation to three reference models with conventional and static building envelopes. In the end, the energy savings made available by the dynamic building envelopes were compared with the three reference models.

MODELING AND SIMULATION

Dynamic building envelopes have different properties that respond to various stimuli (e.g., outside air temperature, indoor air temperature, air-conditioning status, outside solar radiation, etc.). In this research, these variables were utilized as independent variables. With regards to the dependent variables, based on emerging worldwide studies on dynamic envelope materials and construction, we hypothesized four dynamic building envelope properties: R-values of opaque components (walls and roofs, separately), U-factors of windows, and Solar Heat Gains Coefficient (SHGC) of windows. Practically speaking, these hypothesized variable insulation values and window U-factors may not be achievable at this time. However, as indicated above, research has illustrated the rapid progress being made in dynamic materials with variable insulation or SHGC capabilities. The objective of this research is not to evaluate the accuracy and validity of simulations of real dynamic envelopes, but rather to conduct a coupled simulation method in order to access energy savings at the simulation level for the future dynamic envelopes.

Simulation method

In this work, we adopted the EMS of *EnergyPlus* to model and simulate dynamic envelopes. The EMS module was added to the *EnergyPlus* whole-building energy simulation program in version 4.0. It uses the *EnergyPlus* Runtime Language (Erl), a simplified programming language, to set up the advanced control algorithms and scenarios used in the *EnergyPlus* models. The EMS controls and the flexibility of the Erl program allow design engineers to work on novel control strategies related to building systems and construction, options not available with standard *EnergyPlus* control objects; the result is a true whole-building simulation (Ellis et al., 2008). Alongside the development of *EnergyPlus*, recent updates to the EMS actuators now allow them to control more variables such as outdoor air conditions, surface construction, and outside boundary conditions. Three essential EMS elements were used in this work: sensors, actuators, and calling points. This EMS modelling and simulation method are explained and compared to other built-in simulation methods in EnergyPlus in another research work (Wang et al., 2016). The overall framework of this simulation method coupled with the Genetic Algorithm (GA) optimization is shown in Figure 1.

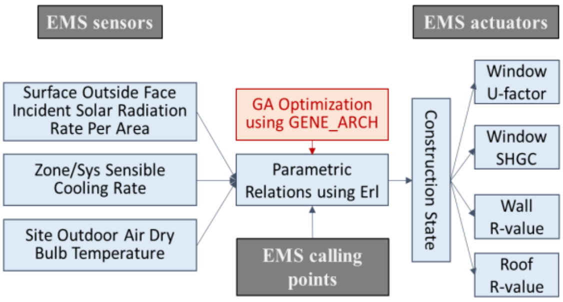

Figure 1. Framework of the parametric energy simulation with a GA optimization

We hypothesized a simple logic between the envelope properties and external conditions. In the EMS environment, we parametrically controlled the windows' SHGC and U values using external temperature, T, solar irradiance on the surface, S, and inside cooling rate, C (relations 1 and 2).

$$SHGC = f(T, S, C), \qquad 1)$$

$$U = f(T, S, C), \qquad 2)$$

Similarly, the wall and roof R-values were also set up through the Erl in EMS (relations 3 and 4).

$$R_{wall} = f(T), \qquad 3)$$

$$R_{roof} = f(T), \qquad 4)$$

Opportunity for optimization

The boundaries of the independent variables in the above relations affect the resulting energy use. Consequently, there is a trade-off issue between the heating and cooling loads. Thus, the values used in this research for the external temperature, solar radiation, and inside cooling rate required an optimization study.

Therefore, in addition to using the EMS of *EnergyPlus*, we also conducted a GA optimization through GENE_ARCH. GENE_ARCH was developed to help architects create energy efficient and sustainable architectural solutions through goal-oriented design, a method that allows them to set goals for a building's performance and have the computer search for a design condition that responds to those requirements (Caldas, 2011). The system can connect to *EnergyPlus* (version 8.0), which serves as the simulation engine. The goal of this research was to find the minimum annual energy consumption, including space heating, cooling, and ventilation loads. In the GENE_ARCH interface employed in service to this goal, the T, S, and C variables in relationships (1) - (4) were set as generating variables; the discretization was determined by the user but the values were automatically generated by the GA. The values generated by the GA were used in the EMS of *EnergyPlus* to generate different envelope properties (the optimal T, S, and C values identified by GENE_ARCH). Theoretically, not only the temperature, solar radiation, and internal system cooling rate boundaries, but also the corresponding thermal conductivity values, SHGC, and window U-factors could be optimized through this GA optimization. However, it would be very time-consuming and complex to perform that large of an optimization study, so this simulation experiment only set the design conditions to be independent variables.

- Modelling of opaque assemblies: In our hypothesis, the insulation of the walls and roofs were set to low thermal conductivity (with higher R-values) when the outside air temperature was too high or low, but at high thermal conductivity (with lower R-values) when the outside air temperature fell to the mild temperature zone. Ideally, in this assumption the walls and roofs enabled the indoor heat gains to be transferred to the outside during the summer cooling period, and maintained the indoor temperature during the winter heating period. This was a simple piece-wise linear relationship between the outside temperature of the material surface and thermal conductivity of the insulation material. The changing boundaries of the external temperature values were searched during the GENE_ARCH GA optimization process. The final identified temperature boundaries for the four selected cities are shown in Figure 2. Building upon this, the overall R-value ranged from 17 to 50 (or 3 to 8.8 in SI units).
- Modelling of dynamic windows: In this study, we expected to go beyond the basic electrochromatic glazing function and explore more controllable dynamic windows. The overall range of the windows' U-factors was assumed to be 0.1Btu/h•ft²•°F (0.01 W/mK) - 0.5Btu/h•ft²•°F (0.07 W/mK), and the SHGC range was assumed to be 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. Again, similar to the opaque element, the changing boundaries of the external temperature, T, and internal cooling rate, C, were identified through the GA optimization using GENE_ARCH. In the built-in EMS actuators, similar to the modelling of the opaque assemblies' dynamic insulation, "Surface" and its "Construction State" option were used to control the input objects "SHGC" and "thermal conductivity" under *EnergyPlus*'s "Fenestration Detailed" section.

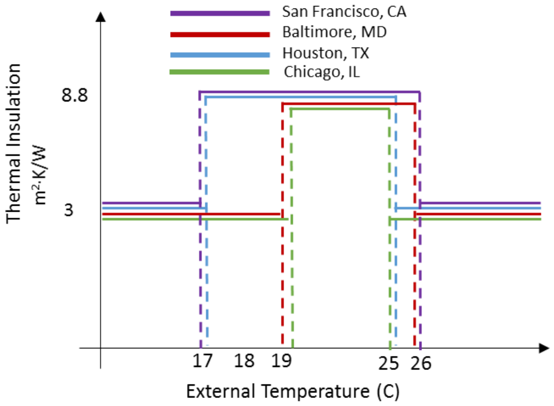

Figure 2. Insulation changes to the walls and roofs with the temperature boundaries for the four cities

Reference models

In order to understand the potential energy savings using these hypothesized dynamic envelopes, we selected a reference model and then conducted several comparisons between dynamic building envelopes and conventional static building envelopes. We utilized a U.S. DOE small office prototype model (see Figure 3) with one floor, 5,500 ft^2 (511 m^2) which complies with ASHRAE Standard 90.1-2013. The reference model's basic geometric information and envelope properties are shown in Table 1.

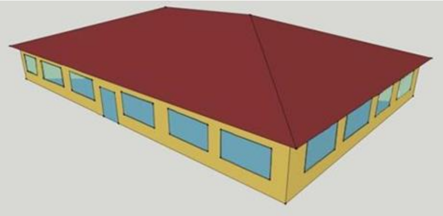

Figure 3. Prototypical office model

Table 1 Basic information on the case study model

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)

The three reference models used in this study include: Baseline Models with minimally code compliant values, using ASHRAE Standard 90.1-2010 (ANSI/ASHRAE/IES, 2010); Advanced Models using the recommendations made in the Advanced Energy Design Guides (AEDG) and developed by the ASHRAE and Technical Support Document (TSD) created by PNNL (with 50% energy savings goals, as compared to ASHRAE Standard 90.1-2010); and Ultra Models, which may be the next generation of energy-efficient technology. They use a "ultra" insulation but have static properties rather than dynamic features. As shown in Table 2, the envelope properties of Ultra Models comply with or are slightly better than the Passive House Guidelines developed by the International Passive House Association (iPHA). In this comparative analysis, the only differences among the reference models and dynamic building envelop models were related to the envelope properties: the insulation of the walls and roofs, and the U-factors and SHGC values of the windows.

In addition, four 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 to represent a range of climates. Table 2 shows the envelope properties of the reference and dynamic envelope models.

DISCUSSION AND RESULTS ANALYSIS

To model the dynamic properties related to the insulation of walls and roofs, SHGC and the overall U-factor of windows, the method of using the EMS actuator called "Surface" and its control variable "Construction State" was used in this study. It also demonstrated the integration of an optimization algorithm (GA) into the feature of the EMS module in *EnergyPlus* to simulate buildings with hypothetic dynamic envelope. The envelope control programs in the EMS module entered to the *EnergyPlus* simulation program and simultaneous changing within these parameters could lead to different envelope boundary settings that could be systematically searched by GA. Similar to other optimization problems, the GA's settings including population size, mutation rate, and others will affect the convergence behaviors (time and power) of the GA. However, due to the goal of this simulation study focusing on the integration of the GA and the EMS method, these GA operators were not examined in this study but will be studied in the future.

Energy use by integrating our hypothesized dynamic envelopes into the reference model was compared with the other three static envelope models to evaluate whether the dynamic envelope behaviors could achieve energy savings as we hypothesized. The following Figure 4 presents the savings percentages of the annual heating and cooling loads of the dynamic

Table 2 Summary of the key building envelope properties of the four models (in IS units)

Climate Zone		**Wall**	**Roof**	**Fenestration**	
		Equivalent R-value	**Equivalent R-value**	**Assembly U-factor**	**Assembly SHGC**
——		h • ft^2 • ° F/Btu	h • ft^2 • ° F/Btu	Btu/h • ft^2 • ° F	——
Baseline Models					
Houston, TX	2A	R-13	R-38	0.81	0.29
San Francisco, CA	3C	R-13	R-38	0.50	0.29
Baltimore, MD	4B	R-13	R-38	0.47	0.43
Chicago, IL	5A	R-13 + R-3.8 c.i.	R-38	0.47	0.43
Advanced Models					
Houston, TX	2A	R-13.0 + R-3.8 c.i.	R-38	0.45	0.25
San Francisco, CA	3C	R-13.0 + R-3.8 c.i.	R-38	0.41	0.25
Baltimore, MD	4B	R-13.0 + R-7.5 c.i.	R-49	0.38	0.26
Chicago, IL	5A	R-13.0 + R-10.0 c.i.	R-49	0.35	0.26
Ultra Models					
Houston, TX	2A	R-75	R-75	0.10	0.10
San Francisco, CA	3C	R-75	R-75	0.10	0.10
Baltimore, MD	4B	R-90	R-90	0.10	0.10
Chicago, IL	5A	R-90	R-90	0.10	0.35
Dynamic Models					
Houston, TX	2A	R-17~R-50	R-17~R-50	0.10~0.50	0.10~0.35
San Francisco, CA	3C	R-17~R-50	R-17~R-50	0.10~0.50	0.10~0.35
Baltimore, MD	4B	R-17~R-50	R-17~R-50	0.10~0.50	0.10~0.35
Chicago, IL	5A	R-17~R-50	R-17~R-50	0.10~0.50	0.10~0.35

envelope models, as compared to the three reference models in the four different locations. The dynamic envelopes produced ~42.6-47.2% savings on the annual cooling and heating loads, relative to the Basic Models. Compared to the Advanced Models, there was ~31.9-44.8% in savings. As was expected, in the Ultra Models, the dynamic building envelopes were still able to achieve ~14.7-20.6% in savings.

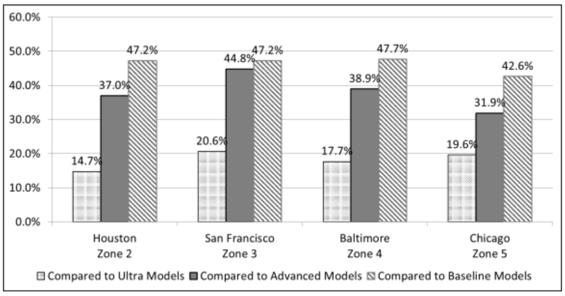

Figure 4. Annual heating and cooling load savings percentages in relation to the three reference models

Obtaining information regarding the peak heating and cooling loads was a necessary step in determining an adequate size for the HVAC equipment. We also documented and compared the peak loads of each of the four models. In our hypothesis, implementation of the dynamic envelopes was expected to reduce both the peak heating and cooling loads. This was verified by the simulation results. In relation to the Basic Models, the dynamic envelopes dramatically reduced the peak heating and cooling demands by an average of 56.4% and 59.4%, respectively, for each of the four cities. Even as compared to the Ultra Models, the average reductions for the peak heating and cooling loads were approximately 24.4% and 30.1%, respectively.

In the end, 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 envelope assembly with regards to savings in the heating and cooling loads. It is important to highlight the contribution to energy savings made possible by single envelope components with dynamic properties, because this may 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 right Figure 5 illustrates that the dynamic envelope assemblies in the Dynamic Models generally achieved more savings than the other three reference models, and that dynamic windows played a more significant role in heating and cooling load savings than did the other envelope components. Savings related to dynamic windows ranged from 30.2~43.9%.

CONCLUSION

This simulation study uses the EMS module in *EnergyPlus* that couples the GA optimization method through the GENE_ARCH platform to analyse the energy performance of the hypothesized dynamic building envelopes. The energy simulation result of the dynamic envelopes compared with the other three reference models with the static envelopes demonstrated that the dynamic properties may achieve significant energy savings in the four selected cities. Also, windows are proved worthy of being made dynamic among all envelope assemblies due to the window’s complex or hybrid impacts on both thermal and visual qualities of indoor environment.

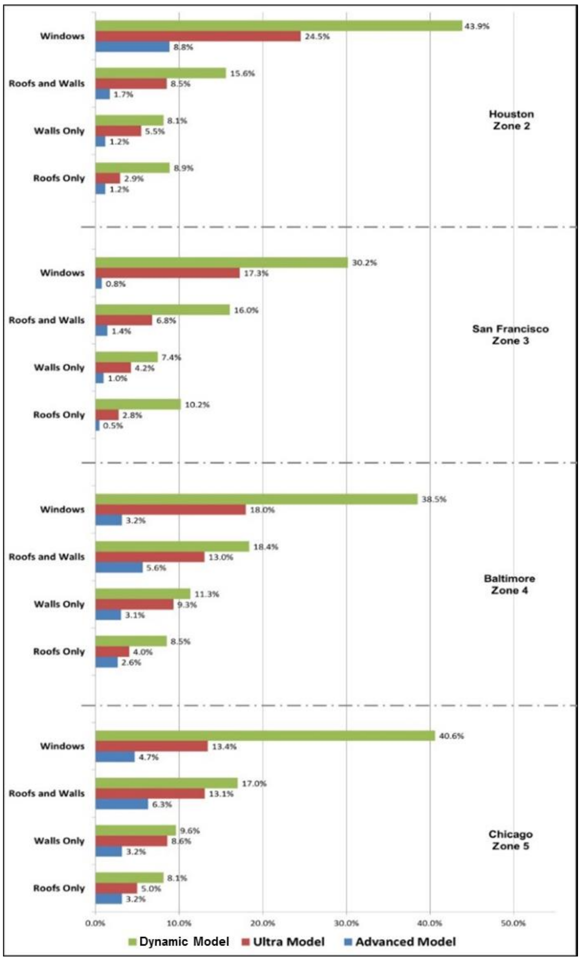

Figure 5. Savings percentages of heating and cooling loads by each envelope assembly, based only on Baseline Models

In this paper, all energy performance and analysis are based on the hypothesized dynamic envelope properties that are only theoretically achievable but have yet to be developed in the real world. However, some important knowledge, such as the contributions of dynamic envelope assemblies on the energy savings, the impacts of different climatic conditions on the performance of dynamic envelopes, and the method of energy modelling and simulation on dynamic envelope properties can be drawn from this comparative study concerning the potential energy savings made possible by dynamic envelopes.

Building upon this research, the future study will focus on more comprehenstive energy analysis in different building typologies and climatic conditions and the GA operators (porpulation size, mutation rate, etc.) for dynamic envelope optimization.

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