Development of Open-Source Parametric EnergyPlus Models and Their Use for Savings Potential Analysis of Envelope Measures

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ABSTRACT

Using the Pacific Northwest National Lab's (PNNL) ASHRAE 90.1–2004 and –2010 EnergyPlus reference models of non-residential buildings as a starting point, an open-source set of highly parameterized generic-building template models and scripts are under development. All US climate zones and one Canadian climate zone, along with three climate types (Humid, Dry, and Marine), are accounted for through 15 representative cities. In addition to the ASHRAE 90.1-2004 and ASHRAE 90.1-2010 benchmark configurations, two high-performance benchmarks are also under development: (EP) "Enhanced Performance", with 50% better energy performance than ASHRAE 90.1-2004; and (HP) "High Performance", with the goal of reaching efficiency levels that make a Net Zero Energy Building plausible. The parameterized models will allow researchers, designers, consultants, building portfolio managers and policy analysts to consider the energy savings potentials of particular efficiency measures in different climates, relative to one of a set of benchmark configurations. A representative medium office building with multiple perimeter and core HVAC zones was used as the starting model. The building features that have been parameterized thus far include: building aspect ratio, window-to-wall ratio (WWR), roof insulation level, wall insulation level, infiltration level, fenestration properties (U-value, solar heat gain coefficient (SHGC) and visible transmission (Tvis)), solar shading, and daylighting controls. Simulation results for various envelope configurations are shown herein, along with a preliminary definition of the envelope configurations for the two high-performance baselines. The parametric simulations also allowed us to isolate the performance impacts of the individual envelope measures relative to the baselines: for example, reducing the WWR to 20% had less impact than moderate improvements to the windows across all climate zones, while altering the aspect ratio to improve daylight penetration had significant impact in the southern climate zones, but very minor savings in the north. Development continues, with the HVAC configurations in the process of being parameterized, and the completed files are due to be made public later this year.

Introduction

Various research groups have previously used energy modeling and scripting to perform large-scale parametric analyses of energy efficiency measures applied to prototypical buildings. A significant example of this is the work by Griffith et al (2007), which simulated vast numbers of efficiency measures applied to a large number of the Commercial Building Energy Consumption Survey (CBECS) 2003 (EIA 2006) building types and climates in an effort to determine how little energy one could use in each case with the best of available technologies, and as a corollary, to find the building types and climates where net-zero buildings would be most feasible. The results of such parametric simulation research with prototypical building models

have been useful in the formation of research and policy plans. Putting this capacity for more analysis into the hands of other researchers, consultants, master planners, portfolio managers, product designers and policy-makers could be even more fruitful, by allowing people to customize the analysis to suit their particular context and questions.

As such, our research has the following objectives:

- *Development of a set of models, scripts and visualization methods for parametric analysis of energy efficiency measures on generic buildings in various climates*. Using PNNL's EnergyPlus models (DOE 2011, Thornton 2011) as a starting point, we are developing a set of model templates and scripts that allow for the simulation of any combination of a large number of features. Large-scale parametric analysis poses new challenges to building simulation users in terms of visualizing and making sense of the vast quantities of outputs, so we are exploring and testing alternate ways of identifying and graphing patterns in the results, some of which are demonstrated herein.

- *Development of a broader set of benchmarks for comparison.* In addition to making very flexible models, we are attempting to define a broader set of benchmark configurations than is commonly used by researchers and practitioners. Four benchmark configurations are considered, representing four performance levels: an ASHRAE 90.1-2004 compliant case, an ASHRAE 90.1-2010 compliant case (roughly 30% more efficient than ASHRAE 90.1-2004), a case ("EP") roughly corresponding to 50% more efficient than ASHRAE 90.1-2004, and a case ("HP") consistent with a net-zero energy building (roughly 65% more efficient than ASHRAE 90.1-2004, with the remainder met by renewables).[1] Having four such benchmarks will allow researchers, product developers and policy makers to consider the potential energy savings from new technologies and other measures applied to buildings of varying base levels of performance. This is valuable since the energy savings attributable to a particular measure is a function of the context; energy savings from sets of measures are neither simply additive nor do measures necessarily interact with one another in a simple way.

- *Quantifying energy savings potential of different types of efficiency measures relative to these benchmarks*. This will be useful information to researchers and policy makers in planning future research and policy directions, by highlighting what types of efficiency measures are likely to make the most significant impact in different climates, for different building types, and versus different benchmarks. Note that the intent of objectives 1 and 2 is to make such analyses of particular efficiency measures easily replicable by other users; we are providing examples.

Our development efforts have been divided into three phases: (a) developing the parametric models / scripts for the envelope systems and performing preliminary analyses en route to defining the two higher performance baselines and determining energy savings potentials of various measures in various contexts; (b) adding lighting systems to the analysis;

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[1] The building parameter configurations for the two high performance levels are not strictly defined a priori, but rather must be determined through our parametric studies. Considering that many building parameters are continuous variables rather than discrete, there are an infinite number of ways of meeting these targets, within some bounded area of the search space (Coffey 2012). In future research we may consider a description of this full set, but in the current work we are using a combination of engineering and economic judgment to define the two cases.

and (c) adding HVAC systems to the analysis. The two high-performance baselines will not be completely defined until the end of phase (c). This paper presents the models and results from the envelope systems phase (a), and some preliminary results from the lighting systems phase (b), showing in the process some of the visualization and analysis methods under development.

This work has been performed in relation to a project performed by the National Institute of Building Sciences and sponsored by U.S. Department of Homeland Security.[2]

Methodology

Parametric Scripting and Template Model Configuration

Starting from PNNL's 90.1–2004 and –2010 Energy Plus models of small, medium, and large office buildings, we are developing a template and scripts that allow the user to construct an EnergyPlus office building model of some particular configuration by simply selecting parameter values. The template EnergyPlus models make extensive use of the EnergyPlus macro language. The scripts are in Python. The overall system may be easily wrapped into a user interface, or may be used to automatically generate and evaluate a large number of parametric modifications.

The PNNL medium-office reference building is a three-story medium office building (shown in Figure 1), of 53,628 gross square feet (GSF). Each floor is modeled as five thermal zones--four perimeter and one core. The floor-to-floor height is 13 ft and floor to ceiling height is 9 ft. The building has an aspect ratio of 1.5:1 and a window-to-wall ratio (WWR) of 33%. The windows are evenly distributed along all the facades with a windowsill height of 3.35 ft and a head height at 7.64 ft. The HVAC system is an auto sized VAV system with a packaged AC unit and gas furnace. The PNNL medium office building files are separated into individual EnergyPlus .idf files based on the ASHRAE standard (90.1-2004 or 90.1-2010) and by 1 of 17 representative climate zone and climate type combinations ("CZ"). Of these 17 CZs, we restricted the analysis to the continental US and Vancouver BC, leaving us with 15 CZs. Table 1 shows the 15 CZs with their representative cities in North America, categorized by climate zone and climate type.

Figure 1. Reference Building

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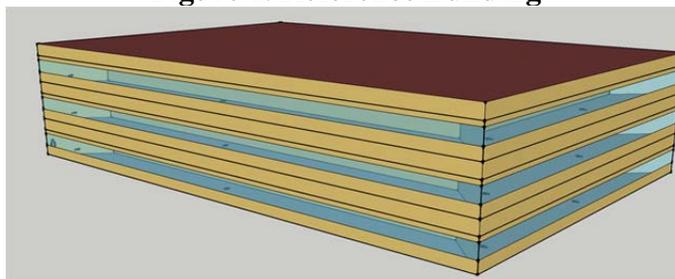
[2] The High Performance Based Design for the Building Enclosure project sponsored by the U.S. Department of Homeland Security, Science and Technology Directorate, Infrastructure and Disaster Management Division, and performed by the National Institute of Building Sciences. The full project report, *BIPS 10 High Performance Based Design for the Building Enclosure* is available at www.dhs.gov/bips under Building Infrastructure and Protection Series Tools and Publications. The Owners Project Requirements Tool developed by the project is available at www.oprtool.org.

Table 1. The 15 CZs Considered, with Representative Cities

A: Moist	B: Dry	C: Marine
1A: Miami, FL		
2A: Houston, TX	2B: Phoenix, AZ	
3A: Memphis, TN	3B: El Paso, TX	3C: San Francisco, CA
4A: Baltimore, MD	4B: Albuquerque, NM	4C: Salem, OR
5A: Chicago, IL	5B: Boise, ID	5C: Vancouver, BC
6A: Burlington, VT	6B: Helena, MT	
7A: Duluth, MN		

These 30 versions of the PNNL medium office building each have slight variations in HVAC system inputs and other inputs. We analyzed the differences across these files, as well as those for PNNL's small and large office building model, and created a single parametric input file for use in generating systematic simulations. A variety of building features were identified, parameterized, and separated into "include" files. These include files are then called from a main .imf file. The main .imf file contains all of the user-defined parameter values for the building configuration under consideration. This main .imf file is written using a Python script that can create individual files or sets of parametric runs for a set of variables. Parameter values for four different benchmarks - ASHRAE 90.1-2004, ASHRAE 90.1-2010, EP ("Enhanced Performance") and HP ("High Performance") – are defined for the 15 CZs and 3 building sizes.

Building Parameters

Thus far, the model and scripts are configured to consider variations in the building geometry and envelope configuration. Selected parameters and their ASHRAE 90.1-performance-level benchmark model values are shown in Tables 2-4 below.

A Note on Weather Files

The original PNNL files come packaged with TMY2 weather files for each location. For our analysis, we used TMY3 weather files. Switching from TMY2 to TMY3 weather files yield differences in energy from -2.0% to 3.4% depending on climate zone (see Figure 2, note that there was no TMY2 weather file available for Vancouver). TMY2 weather files underestimate the solar radiation striking a surface.

Table 2. Model Parameters

Parameter	Allowable Values	90.1-2004 Benchmark	90.1-2010 Benchmark
Building aspect ratio	1.5:1, 3:1	1.5:1	1.5:1
Window to wall ratio (WWR)	20%-60%	[3] 33%	33%
Shading of fenestration	0%-100% Projection Factor (PF)	0% PF	0% PF
Window head height	9 ft, 13 ft	9 ft	9 ft
Daylighting controls	No DL, DL - Stepped Dimming, DL - Continuous Dimming	No Daylighting	DL with Stepped Dimming
Percent of daylighted floor area[4]	~60%, 100%	-	60%
Infiltration levels[5]	0-inf cfm/ft²	0.2 cfm/ft²	0.1 cfm/ft²
Wall R-value[6], Roof R-value, Window U-value, SHGC, Tvis [7]	0-inf, 0-inf, 0-inf, 0-1, 0-1	Climate-dependent, see Table 3	Climate-dependent, see Table 4

Table 3. Climate-dependent Parameter Values for 90.1-2004 Benchmark Model

Parameter	CZ1	CZ2	CZ3	CZ4	CZ5	CZ6	CZ7
Wall R-value	8	8	8	8	12	12	14.5
Roof R-value	16	16	16	16	16	16	16
Window U-value	0.56	0.56	0.56	0.48	0.48	0.48	0.48
SHGC	0.28	0.28	0.28	0.39	0.39	0.39	0.39
Tvis	0.42	0.42	0.42	0.52	0.52	0.52	0.52

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[3] A 40% WWR is the prescriptive level for 90.1 compliance approaches, but the PNNL medium-size office uses a WWR of 33%. Note that as 'benchmark' building models, their aspect ratio and WWR are held constant, whereas in a 'baseline' building model they would change relative to the 'design' model under consideration.

[4] To examine the potential of using daylighting to reduce electric lighting energy use, we expanded on the basic daylighting prescriptive requirements used in PNNL's 90.1-2010 model: we added options for advanced daylighting with continuous dimming and for increased percentage of building floor area using daylighting via (a) higher window head heights yielding deeper daylighting penetration, and (b) an elongated building configuration.

[5] ASHRAE 90.1-2004 does not require use of a continuous air barrier, but ASHRAE 90.1-2010 does.

[6] R-values of the two Standard 90.1 cases were left at the PNNL 2004 and 2010 levels. Feasible values for higher-performance cases were determined in consultation with experts available to our project, and from the Advanced Energy Design Guidelines (AEDG; ASHRAE 2011) 50% for offices.

[7] EnergyPlus does not model windows using U-values, SHGC, and Tvis, but rather a more basic set of metrics, representing the transmission, absorption and reflection in the visible, solar and infrared spectra for each pane of glazing. In order to identify window assembly descriptions that produce the desired rated U-values, SHGC and Tvis values, we used the Window 6 analysis program. We have endeavored to select fenestration assemblies that represent potential fenestration products available in the marketplace rather than creating impossible, theoretical windows. The window options in the template model and scripts include:
•High performance windows, with either low U-Factor values or high Visible Transmittance values, or both
•Dynamic windows, using electrochromic technology with two different types of controllers: Daylighting controllers set to maintain a minimum specified illuminance in the workspace; and glare controllers set to activate when glare levels are above a specified tolerance.

Table 4. Climate-dependent Parameter Values for 90.1-2010 Benchmark Model

Parameter	CZ1	CZ2	CZ3	CZ4	CZ5	CZ6	CZ7
Wall R-value	8	8	12	14.5	14.5	14.5	14.5
Roof R-value	16	21	21	21	21	21	21
Window U-value	0.56	0.56	0.56	0.48	0.48	0.48	0.48
SHGC	0.28	0.28	0.28	0.39	0.39	0.39	0.39
Tvis	0.42	0.42	0.42	0.52	0.52	0.52	0.52

Figure 2. Differences between TMY2 and TMY3 Weather data for 90.1-2010 Model
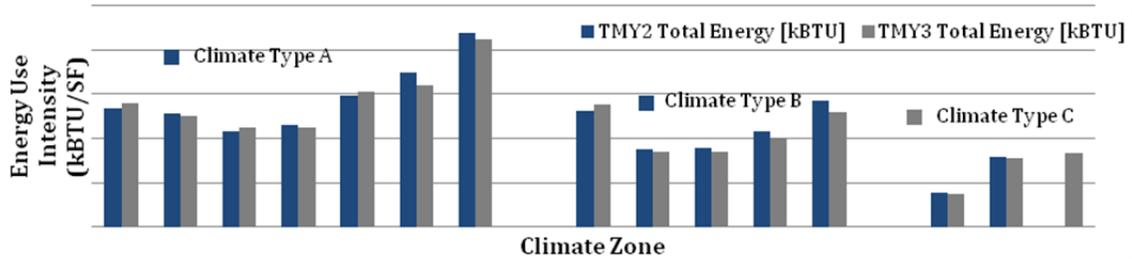
Results of Parametric Simulations for Envelope Configurations
Simulating Many Configurations and Visualizing Results

Figure 3 below summarizes a selected set of simulation results from a large number of envelope variations.

Names given to the configurations are shown on the vertical axis, total building consumption on the horizontal axis. (Note that climate type C is omitted from this chart, as are the Marine climate zones CZ 3 and CZ 5—due to their mild climates they consume significantly less energy than the other climates, and they are removed for visual clarity.) Note that in all of these simulations, only the envelope configuration is being changed. The HVAC configurations are being kept in their CZ-specific ASHRAE 90.1-2010 configurations throughout.

A variety of trends can be viewed in Figure 3. The climate of Duluth (CZ 7A) has consistently the highest energy consumption, Albuquerque (CZ 4B) consistently the lowest. The spread of points in a particular row is instructive: the greater the dispersion of the data points, the less of a general solution that particular strategy is.

The bottom two rows of Figure 3 show the simulation results for two envelope configurations that we are expecting to be their configurations in the two high-performance benchmarks, EP and HP. (The final definitions of these two benchmarks will depend on the effects of the HVAC measures considered). These configurations combine a variety of best performing measures, and are discussed further below.

Sensitivity Analysis: Performance of Particular Measures or Groups of Measures Relative to the ASHRAE 90.1 Benchmarks

One method to reduce loads from the envelope is to lower the WWR; another is to use windows with better U-values and SHGC. To compare these approaches in different climates, we can compare a 90.1-2010 base model with a 20% WWR and base windows against the same model but with 33% WWR and advanced double paned windows, as shown in Figure 4. In this comparison, the model using the advanced double paned windows results in slightly better performance in most climates, but more in cold climates than in warm.

Another interesting result from our simulations is the relatively small reductions found in the southern climate zones from adding external overhangs to the 90.1-2010 model. In the north, adding overhangs is actually detrimental as they block beneficial solar gains that offset the heating load. From our analysis (Table 5), more potential lies with advanced glazing.

Figure 3. EnergyPlus Simulation Results: EUI Per Climate Zone and Simulation Run
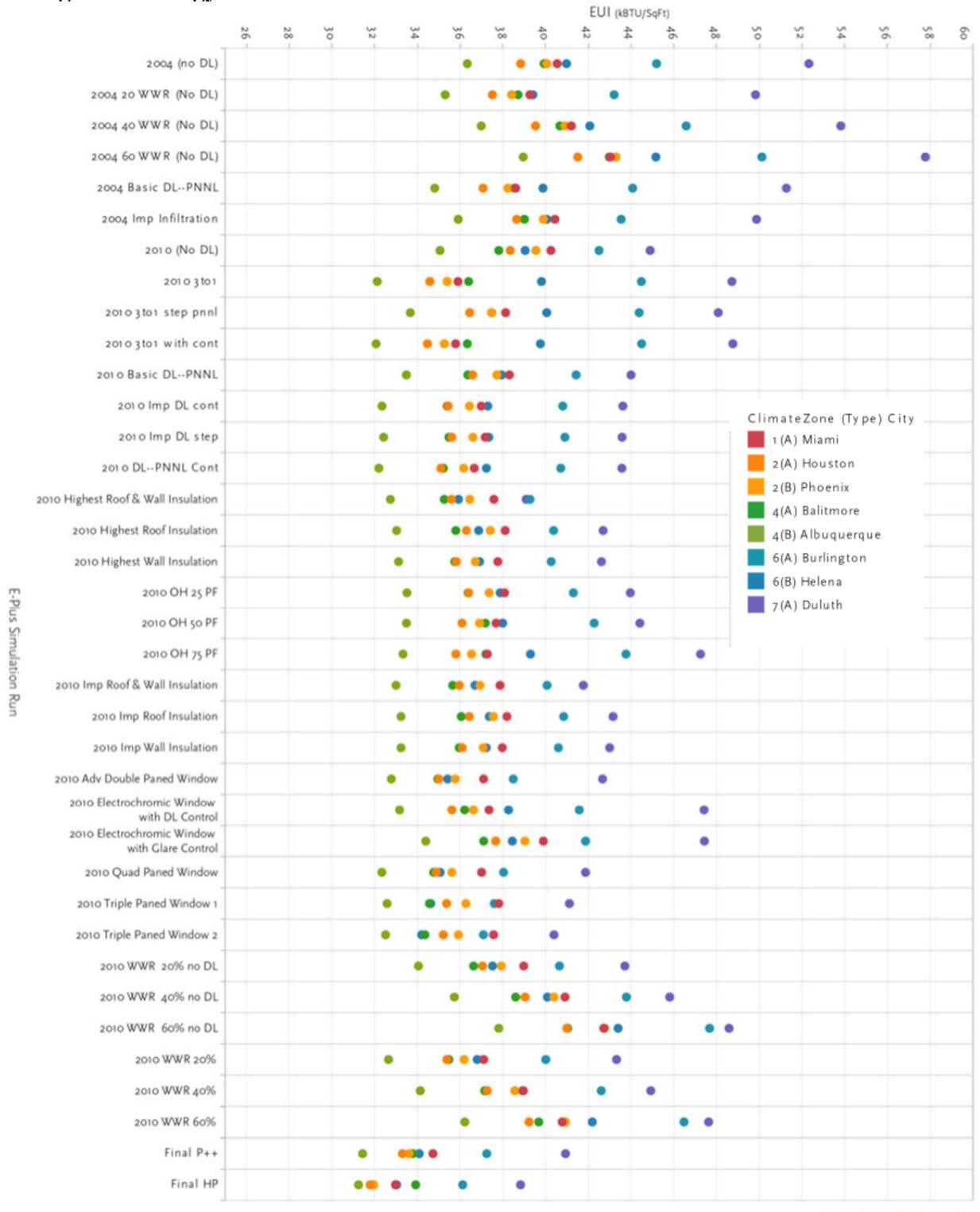
Figure 4. Comparison of 20% WWR (bars on left) and Adv. 2-Paned Windows (bars right)
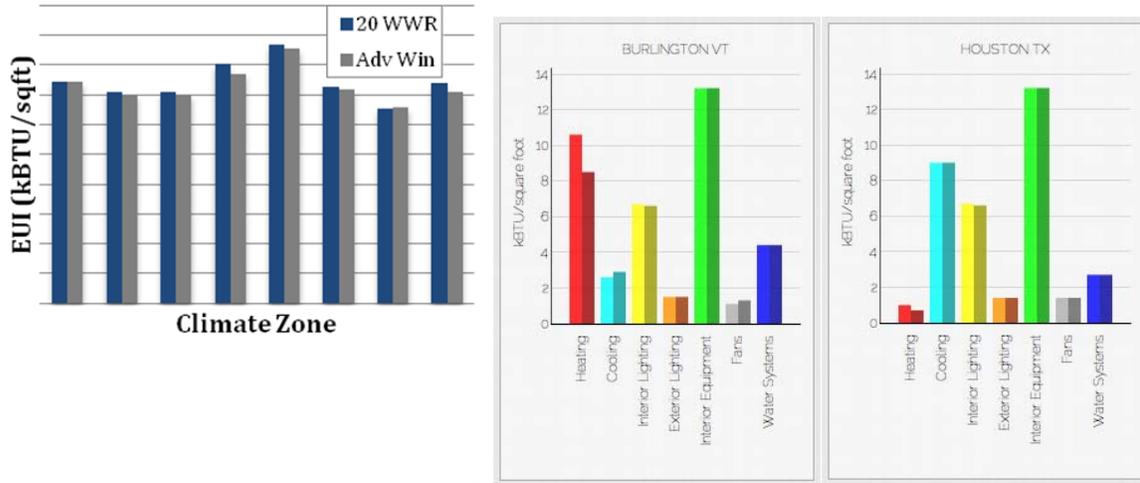
Another potential avenue to increase the daylighting available is by changing the aspect ratio of the building to 3:1 from 1.5:1. This has the effect of increasing the size of the perimeter daylighting zones. In the southern zones, this was the single most effective parameter. It saved almost twice the energy, through daylighting, as increasing the opaque-wall R-values to a maximum reasonable amount (shown in the HP definition below). This does not undermine the need to reduce conduction through the building envelope, especially in the northern climate zones, but it does indicate that prioritizing good daylighting geometries and systems is important.

Table 5. Comparing Windows and Overhang (OH) Performance

Energy Use Per Total Building Area [kBTU/ft²]	Adv. Double Pane	Triple Paned	Quad Solar	Electrochromic (Glare Control)	Overhang 25	Overhang 75
1(A) Miami	37.1	38.9	37.0	39.9	38.1	37.3
2(A) Houston	35.0	36.2	34.9	37.7	36.4	35.8
4(A) Baltimore	35.0	34.8	34.8	37.1	36.4	37.2
6(A) Burlington	38.5	37.6	38.0	41.9	41.3	43.8
7(A) Duluth	42.7	41.1	41.9	47.4	44.0	47.3
2(B) Phoenix	35.8	37.4	35.6	39.0	37.4	36.5
4(B) Albuquerque	32.8	33.0	32.3	34.4	33.5	33.3
6(B) Helena	35.4	34.7	35.1	38.4	37.9	39.3
Percent Savings from 2004 Base	**Adv. Double Pane**	**Triple Paned**	**Quad Solar**	**Electrochromic (Glare Control)**	**Overhang 25**	**Overhang 75**
1(A) Miami	8.5%	4.1%	8.7%	1.6%	6.1%	8.1%
2(A) Houston	9.8%	6.9%	10.2%	3.0%	6.3%	7.8%
4(A) Baltimore	12.5%	13.0%	13.0%	7.1%	8.9%	6.8%
6(A) Burlington	14.8%	16.7%	15.8%	7.3%	8.6%	3.2%
7(A) Duluth	18.5%	21.5%	20.0%	9.4%	16.0%	9.7%
2(B) Phoenix	10.7%	6.5%	11.1%	2.6%	6.7%	8.8%
4(B) Albuquerque	9.8%	9.1%	11.0%	5.3%	7.8%	8.3%
6(B) Helena	13.6%	15.3%	14.4%	6.2%	7.6%	4.1%

Initial Definition of Envelope Measures for High Performance Baselines

We examined the simulation results from a wide range of envelope and daylighting parametric runs and compiled a "best performance" building to provide an initial definition of the HP benchmark model. We also took a set of measures that would be easier measures to implement and compiled them to provide an initial definition of the EP benchmark model. It should be noted that these initial models do not meet the end performance goals for either level, since they do not consider HVAC or lighting improvements, but represent the best envelope measures from our parametric runs. These models demonstrate the performance that can be attained versus the 90.1-2004 and 90.1-2010 benchmark models from envelope improvements only. The configurations are described in Tables 6-8 below.

Table 6. Model Parameters

Parameter	EP Values	HP Values
Building aspect ratio	1.5:1	CZ 1 or 2 = 3:1, otherwise = 1.5:1
WWR	33%	33%
Shading of fenestration	See Table 7	See Table 8
Window head height	9 ft	CZ 1 or 2 = 13 ft, otherwise = 9 ft
Daylighting controls	DL with Continuous Dimming	DL with Continuous Dimming
Percent of daylighted floor area	100%	100%
Infiltration levels	0.1 cfm/ft²	0.1cfm/ft²
Wall R-value, Roof R-value, Window U-value, SHGC, Tvis	See Table 7	See Table 8

Table 7. Climate-dependent Parameter Values for EP Configuration

Parameter	CZ1	CZ2	CZ3	CZ4	CZ5	CZ6	CZ7
Shading of Fenestration	OH, 50% PF	OH, 50% PF	OH, 50% PF?	-	-	OH, 25% PF	OH, 25% PF
Wall R-value	16	16	16	27	27	27	27
Roof R-value	26	31	31	31	31	31	31
Window U-value	0.36	0.36	0.36	0.35	0.35	0.35	0.35
SHGC	0.25	0.25	0.25	0.35	0.35	0.35	0.35
Tvis	0.57	0.57	0.57	0.62	0.62	0.62	0.62

Table 8. Climate-dependent Parameter Values for HP Configuration

Parameter	CZ1	CZ2	CZ3	CZ4	CZ5	CZ6	CZ7
Shading of Fenestration	OH, 75% PF	OH, 75% PF	OH, 75% PF	-	-	OH, 25% PF	OH, 25% PF
Wall R-value	44	44	44	44	44	44	44
Roof R-value	59	59	59	59	59	59	59
Window U-value	0.1	0.1	0.1	0.1	0.1	0.14	0.14
SHGC	0.29	0.29	0.29	0.29	0.29	0.47	0.47
Tvis	0.45	0.45	0.45	0.45	0.45	0.61	0.61

When compared to the 90.1-2004 benchmark model the EP benchmark yields energy reductions on the order of 13.5% to 21.8%. The HP configurations result in reductions from 14.0% to 25.8%. These figures represent savings just from improving the envelope system and adding daylighting controls to the lighting system. Future studies will examine the affect of improved HVAC and lighting systems.

Annual energy results in various climates for the four benchmark models, including EP and HP, are shown in Figure 5. Figure 6 compares the end use profiles of the 90.1-2010 and HP benchmark models for three selected climates. Figure 7 teases apart some the impacts of particular aspects of the HP model configuration.

Discussion

The results from our simulations are presented in this paper in site energy units[8]. For some sets of simulations we have also considered results in source energy units: this generally prioritize reducing cooling load reductions over heating load reductions, which can change the apparent effectiveness of some of the measures tested.

The next steps in our parametric model and scripting development is to add advanced lighting options, to refine our small and large office building configurations (the model is now parameterized to be configurable with any number of stories), and to add a variety of HVAC options. Once these components have been modeled, our EP and HP benchmarks can be redefined to truly represent their desired performance levels.

Figure 5. EP and HP Models Compared to 90.1-2004 (with upgrade HVAC) and 90.1-2010

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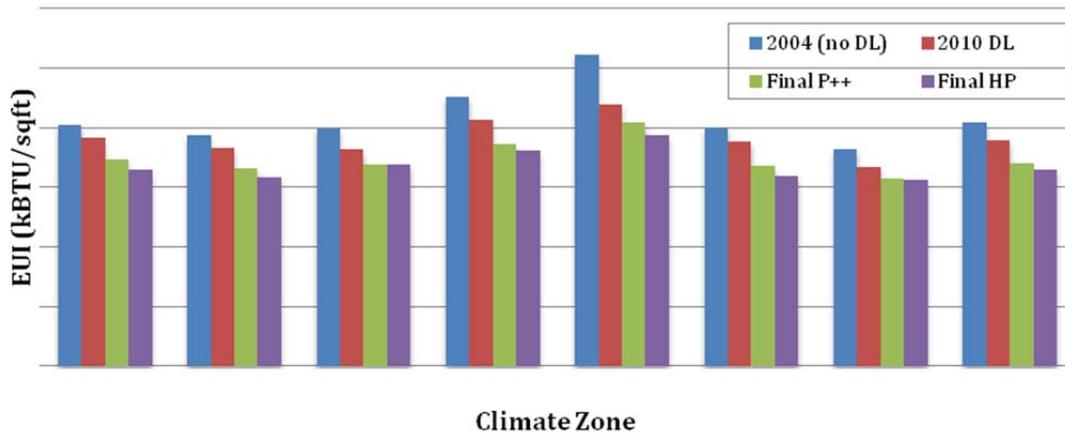
[8] Site energy analysis treats reductions in electricity and natural gas consumption equally. For source energy, however, one unit of site electricity use costs roughly three times as much as on unit of site natural gas use.

Figure 6. Comparison of End Use Profiles in the 90.1-2010 and HP Benchmark Models
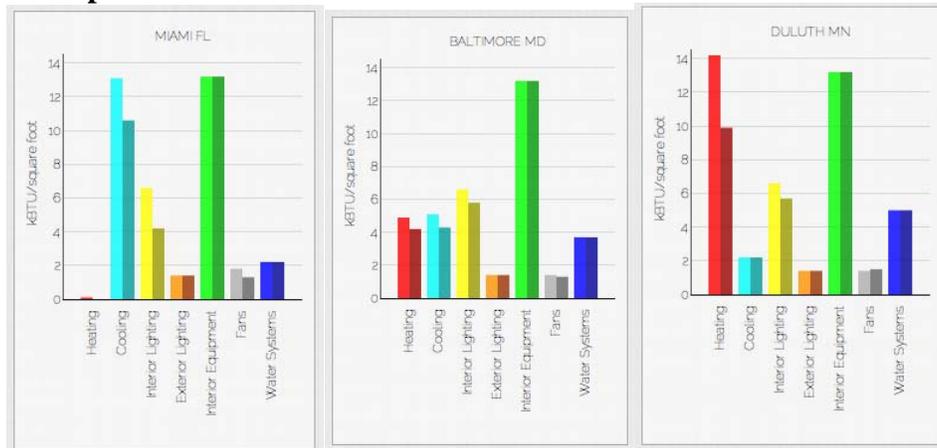
Figure 7. Comparison of HP with Selected Iterations of HP Components
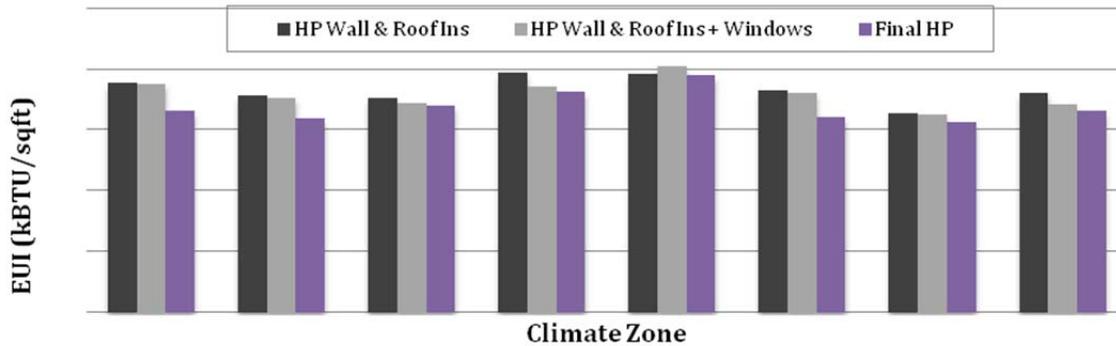
We hope that this parametric analysis toolset and the high-performance benchmarks can be used not only as a tool for policy makers and technology developers considering potential impacts in a variety of climates, but also as a tool for early design framing and decision-making within a particular climate and program context (at both the building and master planning scale): by illustrating the tradeoffs and potential saving of different systems, our models could be used in developing basis of design documents. Further consideration of this use-case is currently under way; it could become an interesting and useful extension of this research project.

Conclusions

An open-source set of highly-parameterized generic-building template models and scripts are under development, which will allow researchers, designers, consultants, building portfolio managers and policy analysts to consider the energy savings potential of particular efficiency measures in different climates, relative to a set of benchmark configurations. In addition to the ASHRAE 90.1-2004 and ASHRAE 90.1-2010 benchmark configurations, two high-performance baselines are also under development. The envelope parameterization has been completed, and simulation results for various cases are shown herein, along with a preliminary definition of the

envelope measures for the two high-performance benchmarks. These models can help assess design trade-offs and the relative gain from different building improvements at different design levels. We hope that the template models, scripts, visualization methods and benchmarks will be useful both for analysis of policies or technologies deployed across various climates and for early-phase analysis of design options for particular buildings and master planning. The tools will be made public in the summer or fall of 2012.

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