SIMPLE BUILDING CALCULATOR

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ABSTRACT

Whole building energy modeling is a powerful tool for analyzing energy use in buildings. For large buildings costs of modeling services can easily be justified due to the significant savings of the implemented measures. For small buildings, the upfront costs of developing robust energy models often deter building owners from investing in energy modeling services. To address this challenge, a *"Simple Building Calculator"* (SBC) was developed. SBC uses pre-simulated results of a range of common measures over a wide range of efficiency inputs. It combines whole building simulation results with statistical modeling techniques to predict energy impact of measures very quickly. In this paper we present the modeling methodology used to develop the data supporting SBC.

INTRODUCTION

According to Commercial Buildings Energy Consumption Survey report over 97% of U.S. commercial buildings are comprised of small buildings i.e buildings with area less than 50,000 square feet (EIA 2012a). Commercial buildings are responsible for a substantial share of the overall U.S. building energy footprint as they consume approximately 61% of total U.S. electricity and 32% of natural gas (EIA 2012b). Hence it is an important sector for focusing building efficiency improvement mechanisms. Today, most small commercial buildings are designed following prescriptive requirements set by building energy codes and quick back of the envelope calculations for estimating building energy use. The simple methods does not consider the building as a single integrated system, but rather views it by its parts, resulting in significant lost energy and energy cost saving opportunities. An alternative approach uses computer simulation conventionally called whole-building energy modeling (BEM) to optimize design. BEM programs produce highly accurate quantitative estimates of annual and peak energy use, allow comparison of design alternatives and enable a data-driven decision-making process. BEM programs take inputs of building characteristics including geometry, envelope, space loads, mechanical systems and building controls; perform physics based calculations of thermal loads and simulate corresponding mechanical system performance (Building Technology Office 2019) to produce overall estimates of building energy use. BEM can be used for analyzing design, comparing efficiency options, showing compliance with regulatory requirements or for predicting energy usage. However, the significant time requirement and expert knowledge needed for its effective use often impede the use of BEM programs in small commercial building applications. Potential solutions (Hart et al. 2016; Rosenberg and Hart 2014) proposed by researchers at the Pacific N orthwest N ational Laboratory (PNNL) include tools based on pre-calculated packages of efficiency measures simulated on prototypical building energy models. It combines the benefits of BEM with the flexibility of a spreadsheet-based simple workflow; allowing simple buildings rapid access to whole building simulation results. This concept was evaluated as an option to improve consistency, adoptability and design flexibility of model energy codes (Hart et al. 2016; Rosenberg and Hart 2014); and was tested in the context of achieving ZNE codes in California (Contoyannis et al. 2018). It utilizes whole building simulation using BEM programs to determine the independent and interactive impact of multiple parameters on building energy use. The simulation results are then used to develop calculation methods with regression formulas. The regressions are packaged in a spreadsheet-based tool capable of creating packages of trade-able efficiency m easures. We a pplied t his concept to develop the *Simple Building Calculator* (SBC), a spreadsheet-based tool for generating relatively accurate and interactive modeling results for small commercial buildings based on a limited but robust set of inputs. SBC will support a range of building types including small to mid sized offices, r etail, s chools, w arehouses, small hotels and mid sized apartment buildings. In its current beta form the tool covers two building types - Office and Retail. In this paper we present the simulation and regression methodology used to develop the data supporting SBC.

ASSUMPTIONS AND METHODOLOGY

For the purpose of this work we consider a simple commercial building as:

- single function building with floor area less than 50,000 square feet,
- is served by a single HVAC system type,
- and has a relatively simple geometry and building fabric.

SBC development process followed these steps:

- Identify commonly desired efficiency options that affect energy operating cost for each building type,

- Identify ranges of parameters for each efficiency option representing vintage to maximum technical potential.
- Complete sets of interactive building model simulations in EnergyPlus for each prototype building in 16 ASHRAE U.S. climate zones.
- Use the simulation results to develop regressions where the parameter values are independent variables and gas, electric use and cost are dependent variables.
- For validation, re-run a sample of packages with the EnergyPlus simulation model to verify regressions.
- Package regressions into interactive spreadsheet tool.

In the following sections we elaborate the modeling and regression methods.

Simulation Framework

The simulations were conducted using two prototype building models (U.S Department of Energy 2018)-Medium Office (MOff) and Stripmall (Rtl).These building types were selected for the beta since they represent a range of simple commercial building functions and are relatively simple and common building types in the U.S. commercial building stock. Pertinent details of the prototype models are provided in Table 1. Simulations were done in EnergyPlus version 9 (EnergyPlus 2018) using a template-based simulation framework that is designed to generate infinite combinations of parameter variables from a single starting point. Details of the simulation framework are described in (Thornton et al. 2012). The simulations were performed in a representative city for each of the 16 ASHRAE climate zones. Weather locations representing each climate zone is shown in Table 2.

Table 1: Prototype Description

	Medium Office	**Strip mall**
Area(sq ft)	53,628	22,500
Aspect ratio	1.5	4
Floor height	13ft	17ft
No. of floors	3	1
Weekday Operation	7 am to 12 pm	9 am to 12 pm
Saturday Operation	7 am to 7 pm	12 am 12 pm
Sunday Operation	7 am to 6 pm	12 am 12 pm
Heat	Gas w electric reheat	Gas
Cool	DX	DX
HVAC air distribution	Variable Volume	Constant Volume

Table 2: Climate Zones and Weather Locations

Zone	**Moisture Regime**	**Weather Location**
1A	Moist	Honolulu,HI
2A	Moist	Tampa,FL
2B	Dry	Tuscon,AZ
3A	Moist	Atlanta,GA
3B	Dry	El Paso, TX
3C	Marine	San Diego,CA
4A	Moist	New York,NY
4B	Dry	Albuquerque,NM
4C	Marine	Seattle,WA
5A	Moist	Buffalo,NY
5B	Dry	Denver,CO
5C	Marine	Port Angeles,WA
6A	Moist	Rochester,MN
6B	Dry	Great Falls,MT
7	NA	International Falls,MN
8	NA	Fairbanks,AK

Measure Selection and Parameter Ranges

For each building type, an efficiency conservation measure list (ECM) was developed. The selection criteria of the measures list included potential impact on building energy use, applicability or popularity in real buildings and feasibility of accurately modeling the measure in EnergyPlus. Another criteria was covering all major end-uses within each building type. After the ECM list for each building was developed, we identified the range of parameters (Lvls) to consider for each efficiency measure that could represent vintage to maximum technical potential for each measure type. For some items, such as federally mandated equipment efficiency, a reasonable 15 year past code level was the floor. For each measure, Lvl1 represents the least efficient option and each higher Lvl number represent increments in increasing efficiency. ECM's included in the analysis and inputs for each level of the efficiency parameter range are presented in Table 6. For each ECM, a typical case was also modeled. The typical case is roughly representative of a reasonable efficiency level of a similar building in compliance with building energy code (90.1-2016). Table 5 lists the efficiency level of each measure corresponding to the typical case. Details of each efficiency measure are discussed below.

1. *Glazing to Envelope Ratio (GER):* is the ratio of the total glazing area to total above grade envelope area

of the building. GER is calculated as:

$$GER = \frac{A_f}{A_e} \tag{1}$$

$$where, A_f = A_{window} + A_{skylight}, A_e = A_{wall} + A_{roof} \tag{2}$$

Window and skylight areas in the prototype models were modified to meet the GER efficiency levels. Range of modeled GERs and corresponding window to wall area ratios (WWR) and skylight roof ratios (SRR) for each GER level are listed in Table 6

2. *Envelope Heat Loss (UAvg):* is the overall heat loss through the envelope assembly represented by the calculated weighted average of U factors of opaque wall, roof and fenestration assemblies. For modeling this measure, the U factor of each envelope object was modified to various levels of U factors as shown in Table 6.

$$U_{Avg} = \frac{(U_w * A_w) + (U_r * A_r) + (U_f * A_f)}{A_w + A_r + A_f} \tag{3}$$

3. *Air leakage (Airleak):* this measure represents the air leakage through the exterior envelope assembly in cfm/sf @ 75 pascals and includes leakage through above and below grade building envelope. The modeled air leakage rates are adjusted for standard wind conditions as described in (Gowri, Winiarski, and Jarnagin 2009) and are modeled at four levels as detailed in Table 6.

4. *Solar Heat Gain (SHGC):* is the heat gained through glazed portions of the envelope assembly modeled by varying the fenestration SHGC input. The range of efficiency levels evaluated took into consideration most and least efficient window technologies in the U.S. market.

5. *Lighting Power Density (LPD):* is the power density of interior lights. In the Office model, LPD is modeled as ambient lighting and in the Retail model, interior lights are split into ambient and display lights as detailed in Table 6.

6. *Daylight Controls (Adl):* This measure is the % of the floor area with daylight controlled lights that dim in response to daylight availability in the space. To model this measure the floor area with daylight controls was modified in the original models from 0% to maximum levels. In higher levels, skylights were added. *DaylightControl* object in EnergyPlus were used to set controlled fraction of zone area and for controlling the dimming fraction of electric lights.

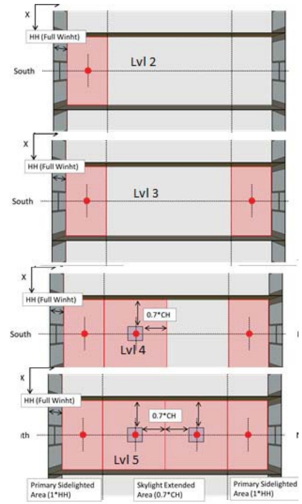

Figure 1: % of Floor Area with Daylight Controls for Level 2,3,4 and 5 in Retail models

Figure 6 illustrates the fractions of space areas controlled with daylight controls at each level of the Adl measure.

7. *Occupancy Lighting Controls (Aos):* this is the percentage of floor area with occupancy sensor controlled lights. Since there are technical limitations in the use of occupancy sensors in certain space types and the savings potential of occupancy sensors varies by building application; the measure was modeled based on available literature on occupancy sensor savings (VonNeida, Maniccia, and Tweed 2000). Space types considered for this measure and estimated savings from occupancy sensors in each space type are documented in Table 3. To model this measure the lighting schedule in the prototypes were adjusted. For each level, the % of lights in the applicable space types per Table 6 were modeled with an adjusted lighting schedule as shown in the example in Figure 7.

8. *ERV Effectiveness (ERV):* This ECM models the effectiveness of the energy recovery equipment. It is modeled by using the *HeatExchanger:AirtoAir:SensibleandLatent* object in EnergyPlus. For each level ERV effectiveness is varied as shown in 6 by changing the *sensible and latent effectiveness* fields and the associated fan energy modeled as the wheel parasitic power using the *Nominal Electric Power field* of the same object. Lvl 1 ERV effectiveness of 0% represents a case with no energy recovery.

9. *Cooling Equipment Efficiency (CoolCOP):* is the

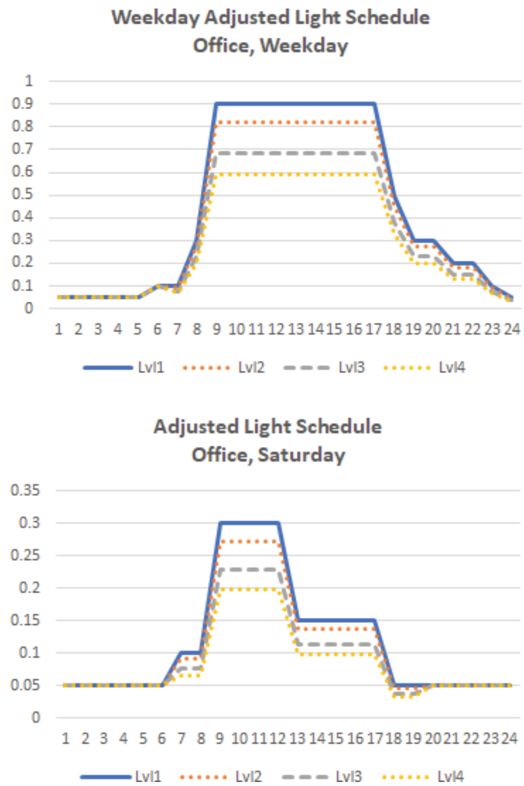

Figure 2: Lighting Schedule Adjustment in Office prototype for Aos measure

Table 3: Estimated Lighting Energy Savings from Occupancy Sensors

Space Type	Est. Savings
Office-open plan	35%
Office-enclosed	38%
Corridor	55%
Conference	44%
Stairway	15%
Restrooms	60%
Storage	60%
Lounge	15%
Dining	15%
Classroom	43%
Retail	15%

rated efficiency of the space cooling equipment.

10. *Heating Equipment Efficiency (HeatEt):* is the rated efficiency of the space heating equipment.

11. *Fan Power (FanPwr):* is the total Fan Power in W/cfm calculated as:

$$FanPwr = \frac{Fan_{SP} * 745.7}{Fan_{ME} * Fan_{CF} * 6356} \quad (4)$$

12. *Fan Control (FanCtrl):* This parameter models difFerant kinds of fan operation. For the Office model it is the minimum fan turndown for variable airflow rate. For the Retail, this parameter can represent a on-off, cycling, two-speed, three-speed or variable flow fan.

13. *Economizer Lockout (Econ):* in this measure economizer lockout options are analysed. It is modeled with a *FixedDryBulb* economizer in the *Controller:OutdoorAir* object. The maximum dry bulb temperature limit is varied as shown in Table6.

14. *% of Design Outside Air (OSA):* This measure simulates the average annual % of design outside air when the space is occupied. VAV systems require more system air than the zone requirements. To model the range of efficiencies for this measure, design Outside air rates calculated per the ASHRAE 62.1 requirement for outside air were modified as shown in Table 6, OSA in the *DesignSpecification:OutdoorAir* object.

15. *Plug Load Reduction (Plug):* this measure includes strategies for reducing plug load consumption in buildings. For Office and Retail buildings we assumed that at least 50% of all 125 volt 15- and 20-ampere receptacles installed in private offices, open offices, conference rooms, breakrooms, individual workstations and classrooms will have controlled receptacles capable of turning the receptacle power off during unoccupied hours or when no occupants have been detected for more than 20 minutes. To model the various levels, we assume % of floor area with 50% plug load control per the values in Table 6. This measure is modeled by adjusting the plug load equipment schedule as shown in the example in Figure 3.

16. *VAV Reset (Vrst):* This measure simulates VAV reset control options. It combines two reset strategies-outdoor air based supply air temperature reset and fan static pressure reset. The temperature reset is modeled using the *SetpointManager:OutdoorAirReset* object; when the outdoor air temperature is greater than 70 degrees. The reset temperature differences are various efficiency levels are shown in Table 6. Fan static pressure reset is expressed as a Boolean (0-No, 1-Yes) in Table 6 and is modeled by changing the fan power coefficient inputs as shown in Table 4.The input range

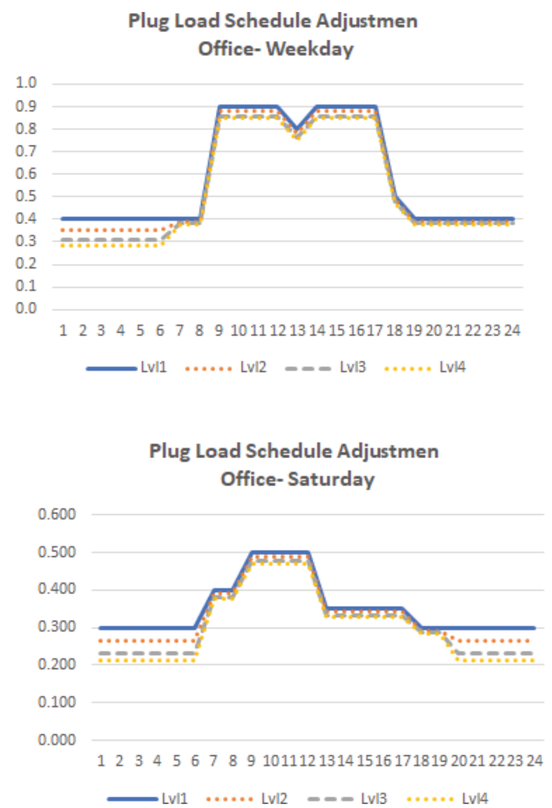

Figure 3: Plug Load Schedule Adjustment- Office

Vrst in Table 6 is expressed as a score calculated as a sum of Temperature (F) and pressure reset setting. This measure was simulated only in the Office model since the Retail prototype does not have a VAV system.

Table 4: Fan Coefficients for SP Reset

	No Reset	SP Reset
Fan Power Coefficient 1	0.070429	0.040759894
Fan Power Coefficient 2	0.38533	0.08804497
Fan Power Coefficient 3	-0.46086	0.07292612
Fan Power Coefficient 4	1.009203	0.943739823
Fan Power Coefficient 5	0	0

17. *Zone Minimum (ZnMin):* is the VAV box minimum that sets the minimum airflow to the zone. High minimum airflow setpoints result in inefficiencies by forcing too much supply air from the central airhandler resulting in higher reheat for maintaining the temperature zone setpoint. This measure does not apply to Retail building model.

18. *Extra Fan Operation (FanExtra):* This measure simulates the additional hours the fan and outside air dampers are on for warmup or after regularly occupied hours on weekdays as shown in the example in Figure 4.

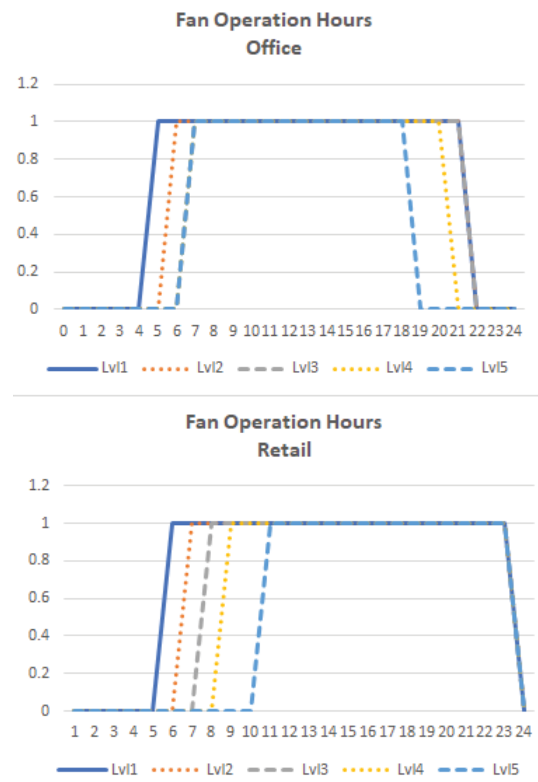

Figure 4: Fan Operation Schedule Adjustment

ECM Combinations

In addition to simulations of individual ECM levels in each climate zone, 38 ECM combination sets as shown in Table7 were simulated to capture the interactive impacts of each measure. The combination runs included All ECM's at each individual level; Mixes of Envelope, Interior Load, Light or HVAC measures with other category measures held constant at baseline level and finally a mix of all measures at varying level combinations. ECM combination runs and number of combinations sets are listed in Table 7.

Simulation Quality Control

For each building type approximately 10,000 individual EnergyPlus simulations were run. To ensure accuracy of simulation inputs and outputs, custom quality control

Table 5: ECMS and Typical Levels

Measure	Off	Rtl
Glazing to Envelope Ratio	Lvl3	Lvl4
Envelope Heat Loss	Lvl4	Lvl4
Envelope Air leakage (cfm/sf @ 75Pa)	Lvl3	Lvl3
SHGC	Lvl4	Lvl3
Lighting Power Density	Lvl4	Lvl3
Daylight Controls	Lvl2	Lvl1
Occupancy Controls	Lvl3	Lvl1
ERV Effectiveness	Lvl1	Lvl1
Cooling Efficiency	Lvl3	Lvl3
Heating Efficiency	Lvl3	Lvl3
Fan Power	Lvl3	Lvl3
Fan Control	Lvl3	Lvl1
Economizer Lockout	Lvl4	Lvl4
% of Design Outside Air	Lvl2	Lvl2
Plug Load Control	Lvl3	Lvl3
VAV Reset	Lvl4	NA
VAV box minimum	Lvl3	NA
Fan Operation Hours extra	Lvl4	Lvl3

workflows were devised using Python scripts and graphical tools in Excel. Python scripts were used to quickly compare multiple EnergyPlus idf input and html output files concurrently. It singled out the differences in a selection of files for rapid error checking. Custom made graphs in Microsoft excel aided visual inspection of result trends of efficiency measures as shown in an example in Figure 5.

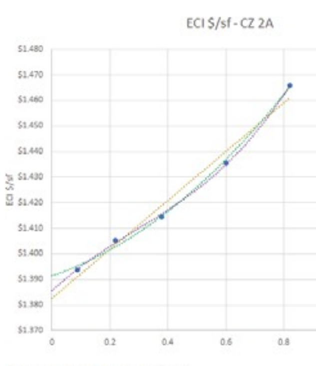

Figure 5: SHGC simulations in Climate Zone 2A

Regression Development

The EnergyPlus results were used to develop regressions where the parameter values are independent variables and gas and electric use are dependent variables, with the following rules:

Table 6: ECM Parameter Range

ECM	Bldg.	Lvl1	Lvl2	Lvl3	Lvl4	Lvl5
GER	Off	48%	25%	19%	6%	19%
WWR		90%	48%	36%	12%	36%
SRR		3%	0%	0%	0%	0%
GER	Rtl	29%	27%	9%	5%	
WWR		75%	75%	28%	14%	
SRR		3%	0%	0%	0%	
U-avg	Off	0.66	0.41	0.17	0.10	0.07
	Rtl	0.66	0.39	0.11	0.06	0.04
WallU	All	0.46	0.28	0.12	0.06	0.02
RoofU	All	1.28	0.42	0.06	0.03	0.03
WindowU	All	1.02	0.80	0.57	0.36	0.30
Airleak	All	2	1	0.4	0.15	
SHGC	All	0.82	0.60	0.38	0.22	0.09
LPD	Off	4	2	1	0.66	0.25
Base	Rtl	3	2.15	1.3	0.65	0.65
Display	Rtl	1.5	1.05	0.6	0.3	0
Adl	Off	0%	27%	41%	60%	61%
	Rtl	0%	22%	44%	78%	100%
Aos	Off	0%	48%	66%	88%	
	RtlS	0%	20%	35%	50%	
ERV	All	0%	10%	50%	70%	85%
Sensible		0%	45%	67%	80%	91%
Latent		0%	0%	36%	65%	90%
FanPower		0	0.22	0.41	0.51	0.55
CoolCOP	All	2.5	3.0	3.9	5.6	
HeatEt	All	0.65	0.75	0.81	0.98	
FanPwr	Off	2.01	0.91	0.53	0.21	
	Rtl	2.38	1.49	0.62	0.24	
FanCtrl	Off	1	0.66	0.5	0.15	
	Rtl	CV	Cycl	2-Spd	3-Spd	VFD
Econ	All	50F	60F	65F	70F	75F
OSA	Off	200%	133%	118%	100%	50%
	Rtl	133%	118%	100%	50%	
APlug	All	0%	34%	68%	85%	
Vrst	Off	0	5	8	10	13
ResetTemp		0	5	7	9	12
SPReset		0	0	1	1	3
ZnMin	Off	50%	40%	30%	20%	5%
FanExtra	All	3	2	1	0	-2

- Separate regression coefficient sets are developed for each HVAC system type in each climate zone.
- Separate regression equations are developed for each energy type with some separation by end use: general electric; cooling, auxiliary HVAC electric; electric or gas heat; and other gas are all separate regression equations. This was found necessary to main-

Table 7: ECM Combinations

Name	Type	No. of Run sets.
All	All	4
Mix	Env	5
Mix	Load	3
Mix	Light	3
Mix	HVAC	6
Mix	ELH	18

tain significance and keep results comparative between different heating types.

- All option parameters are retained as independent variables in at least one of the energy type equations, even if their significance is low. In regressions for the non-primary energy type (e.g., the gas interaction with lighting), insignificant variables are dropped.

- Interactive variables or second- and third-order variables are included where there is a logical justification and they improve either the R-correlation or overall building regression projections compared to the simulated results.

The R correlations (Multiple R2) are quite high, ranging from 0.943 to 0.999 for the mid-sized office. When regression coefficients were used to calculate the ECI results from inputs for the simulation runs, the comparison was very close, with 86% of regression results within 3% of simulated cases and 97% within 5%.

Results and Discussion

Major findings of the simulation results are discussed here. For brevity, we present the findings of the simulations from three U.S. climate types- warm (2A), mild (5B) and cold (7) in this paper.

- In both building types the ECM parameters that resulted in highest building energy cost (ECI) when compared to the typical case across all three climate zones were *Envelope heat-loss* and *Interior Lighting Power Density*, likely because worst case vintage buildings were included.

- *Envelope heat-loss* and *Interior Lighting Power Density* were also the top two measures that resulted in the widest range of building energy cost in both building types.

- ECM's that resulted in lowest building energy cost varied by building type and climate zone. In the Office models, the *Zone Minimum* measure parameters resulted in least building energy cost in the cold and mild climate zones. Higher efficiency levels in the *Interior Lighting Power Density* and *Cooling Equipment Efficiency* measures resulted in lowest building energy costs in the mild and warm climate zones. In the Retail models, higher efficiencies in measures *Air leakage* and *Heating Equipment Efficiency* resulted in least ECI in cold climates and *Lighting Power Density* and *Daylighting Control* measures resulted in least ECI's in both mild and warm climates.

The relative impact of each ECM variable tested in Office and Retail models for climate zones 2A and 7 are presented in Figure 6 and Figure 7. The vertical line represents the typical case, while the orange bars to the right show increased energy cost with the worst case, and bars to the left show reduced energy cost with the best case. The tornado diagrams in Figures 6 and 7 are helpful in understanding which measures have the largest impact on building energy use.

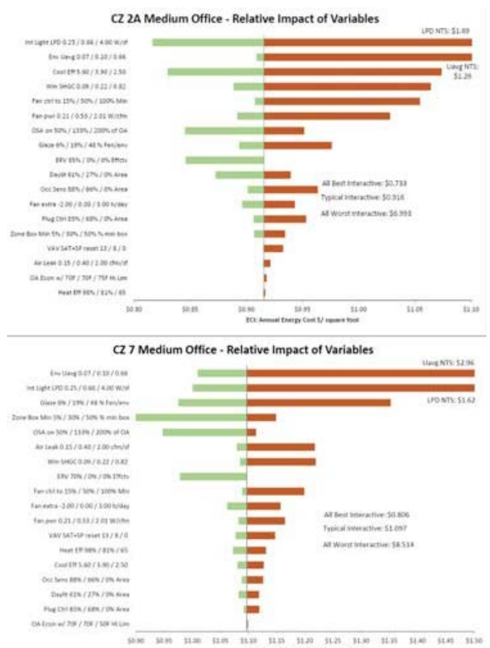

Figure 6: Relative Impact of Variables: Office, Climate Zones 2A, 7

Applications

The Simple Building Calculator will provide building designers an easy to use tool for quickly evaluating various combinations of efficiency measures. While the tool is not intended for precise results, it will compare interactive impact of various measure combinations. The tool can be used for evaluating efficiency options for schematic design of new construction and for early program or retrofit project designs. It can also be used for measure compar-

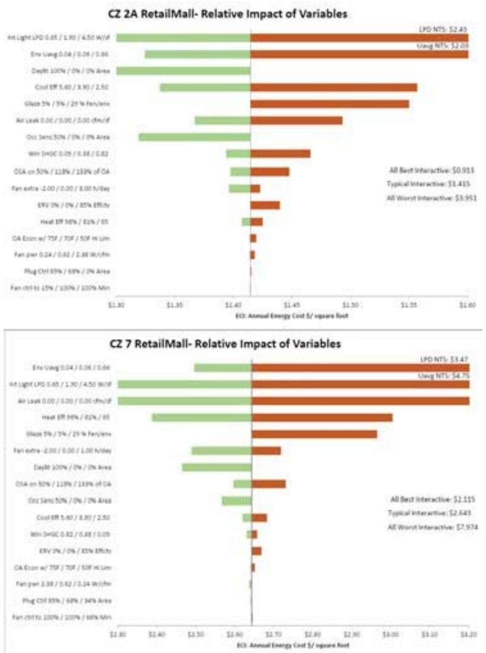

Figure 7: Relative Impact of Variables: Retail, Climate Zones 2A, 7

ison, development of multiple measure package combinations, or verification that measure combinations meet efficiency targets.

Conclusion and Next steps

Simple Building Calculator gives building owners and designers an option for data-driven decision making using a simple spreadsheet-based tool. It makes interactive savings calculations of building and climate specific efficiency measures or measure packages readily and quickly available for small commercial buildings. With the beta version of the SBC tool we were able to test the underlying concept and develop the simulation and regression methodologies required for the tool development. Next steps include expansion of simulation and regression framework to include more building and HVAC system types, validation of regression models, improving font-end of the tool and finally field validation.

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NOMENCLATURE

U_w	U value of opaque walls in Btu/ft^2Fhr
A_w	Area of opaque walls in ft^2
U_r	U value of roof in Btu/ft^2Fhr
A_r	Area of roof in ft^2
U_f	U value of fenestration in Btu/ft^2Fhr
A_f	Area of fenestration in ft^2
Fan_{TE}	Fan total efficiency
Fan_{ME}	Fan motor efficiency
Fan_{CF}	Fan mechanical efficiency
Fan_{SP}	Fan static pressure in inches of H_2O
$FanPwr$	Fan Power in W/cfm

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