Building and System Level Sensitivity Analysis to U.S. DOE Commercial Reference Office Building in Different Climate Zones

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ABSTRACT

Dynamic whole building energy models (BEMs) are created for various reasons: to evaluate alternative design strategies; compliance checks with energy codes; apply certifications at the design stage of a new building; continuously improve building performance through its life cycle; assist decision making on implementation of energy conservation measures (ECMs). For quantitative guidance, BEM has to be carefully calibrated to reflect a building's actual operation conditions. Given that even a simplified model would normally comprise hundreds of inputs, reconciling a specific BEM to a particular building system's measured energy use is tedious, time-consuming, labour-intensive and without a guiding protocol methodology. Consequently, developing a concise list of parameters that have the greatest potential to impact the performance of critical building subsystems is the first and crucial stage in tuning a BEM. This study demonstrates a methodology of using prototyped, "newly constructed" medium office building EnergyPlus models, developed by U.S. Department of Energy (DOE), known as the DOE commercial reference buildings, with representative characteristics of numerous building types in U.S. market. By relating the reference buildings to the variety of existing building types in the U.S. building stock, these reference buildings serve as baseline models to establish a guiding parametric list. Key model input parameters are first selected by qualitatively analysing subsystem models. Each parameter is perturbed, while others remain unchanged relative to the base model values. The whole building annual energy use and subsystem energy use are outputted for each simulation run and compared to the baseline model results. After both building and subsystem level input-output sensitivity coefficients are calculated for each perturbation, all variables are prioritized according to the relative importance based on the degree of influence on outputs. Similar analyses are repeated in sixteen (16) cities/climate zones throughout U.S., generating the prioritized parameter lists for comparison. When tuning office building models with comparable size and system types in practice, those variables identified as having the greatest influence are earmarked to be validated through onsite measurement, sub-metering, or surveys. Such a prioritized key parameter list focuses designers' attentions on the modelling assumptions or default values of

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important variables that can lead to the discrepancies between simulated and actual building energy use.

KEYWORDS
Sensitivity Analysis, DOE Reference Buildings, Building Energy Model Calibration

INTRODUCTION

Two distinctive paths towards reconciling BEMs to the measured are identified from previous research investigations (Reddy et al. 2006): the manual, heuristic approaches, which normally contain field measurements, "trial-and-error" scenarios, with the result that the model accuracy is largely dependent on modellers' experience and engineering judgements (Kaplan et al. 1990, Waltz 1992, Norford et al. 1994, Haberl and Bou-Saada 1998, Yoon et al. 2003, Pan et al. 2007); the mathematic, analytical methods, which essentially treat the building energy model calibration problem as a special, under-determined optimization problem and search methods are deployed to find the most-fit combination of independent variables to minimize the difference between simulation results and measured energy use (Carroll and Hitchcock 1993, Lee and Claridge 2002, Reddy et al. 2006). Sensitivity analysis (SA), defined as a study of how uncertainty in the output of a model (numerical or otherwise) can be apportioned to different sources of uncertainty in the model input (Saltelli et al. 2008), has been included in both categories of model calibration approaches to differentiate parameters having different levels of impact (Westphal and Lamberts 2005, Reddy et al. 2006).

Among three sensitivity analysis techniques-differential sensitivity analysis (DSA), Monte Carlo analysis (MCA), and stochastic sensitivity analysis (SSA) used for building thermal simulation programs (Lomas and Eppel 1992), DSA is probably the most popular and widely-used methodology due to its simplicity and straightforward application process (Spitler et al. 1989, Corson 1992, Lam and Hui 1996, Mottillo 2001). Other SA techniques (Petr et al., 2007, Burhenne, et al., 2010, Eisenhower, et al., 2011) related to building energy models are also extensively documented in the literatures.

In this paper, the DSA method is chosen to distinguish the relative significance of carefully-selected inputs of a DOE reference medium size office building acting as an "existing building." Parameters are then arranged in the descending order of the calculated sensitivity coefficients for each building system and for representative U.S. climate zones, as well.

RESEARCH METHODS

The U.S. DOE commercial reference building models include 16 building types in 3 vintages (new construction, post-1980 construction, and pre-1980 construction) representing approximately 70% of the commercial buildings in U.S. market (Anon). A "newly-built" medium size office building is selected to demonstrate the methodology used in this paper. Figure 1 shows the building aspect ratio and the thermal zoning layout for a typical floor. It is a three-floor, rectangular building with gross floor area of 4982 m^2. Each floor is divided to five thermal zones-four perimeter zones and an interior zone as shown in Figure 1. The plenum space on each floor is simulated separately as an unconditioned zone. Three variable air volume (VAV) systems equipped with Direct-Expansion (DX) units for cooling and gas-furnaces for heating serve the entire building. Several parameters, such as building envelopes, economizer control strategy, etc., of each model in the different climate zones are developed based on ASHRAE Standard 90.1-2004. Thus they are slightly different from each other. In order to make the SA results consistent, a medium office building within climate zone 4A is picked as the base model and simulated with different weather files. Deru et al. (2011) documented more details of the EnergyPlus model.

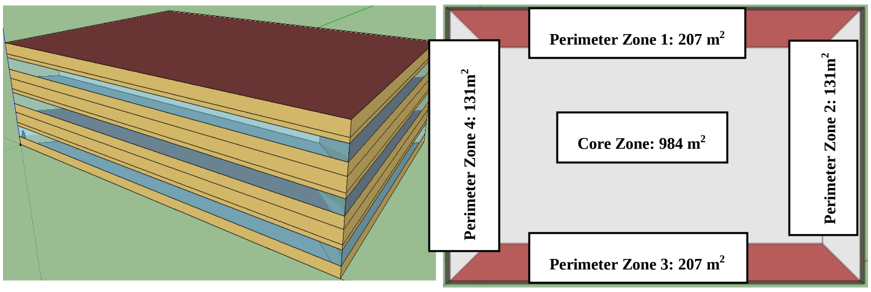

Figure 1. *Medium office building (left) and thermal zones of a typical floor (right)*

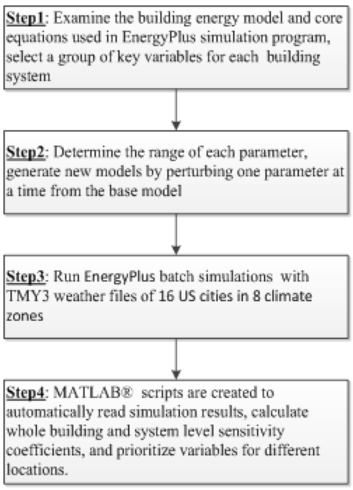

Figure 2. *Procedure of conducting system level sensitivity analysis*

The overall SA procedure proposed in this paper is shown in Figure 2. The sensitivity coefficient used to differentiate the relative importance of numerical variables is defined as the percentage change of the output divided by the percentage change of the input, both relative to the base value. In this paper, the interested simulation outputs include whole building annual electricity and gas energy uses, as well as interior lighting, exterior lighting, plug load equipment, fan, cooling subsystem, heating and domestic hot water (DHW) gas energy uses.

$$SensitivityCoefficient(SC) = \left|\frac{\Delta O}{\Delta I}\right| = \left|\frac{\left(\frac{O_{pert} - O_{base}}{O_{base}}\right)}{\left(\frac{I_{pert} - I_{base}}{I_{base} - I_{\min}}\right)}\right| \tag{1}$$

Where O_{base} and I_{base} are the base model output and input, respectively;

O_{pert}, I_{pert}, and I_{min} are the perturbed model output, input and potential minimum value of input, respectively.

Table 1 lists selected investigated parameters, abbreviated names, and the perturbed percentage changes to the base values. The last column differentiates whether the variables of interested are is determined during design (D), associated with building operations (O) or specifically the building system control (C) stradegies. Note that economizer control, reheating and cooling enable/disable controls are also involved in this study. The percentage changes of these parameters are assumed to be 100 to enable comparison with other numerical varialbes. An example of schedule change is shown in Figure 3.

Table 1. *Summary table of studied variables*

	Index	Parameter Full Name	Abbrev. Name	Percent Change (%)	Category
Interior Lighting System	1	Lighting Power Density (W/m^2)	LPDIL	50	D
	2	Interior Lighting Schedule	SCHIL	50	O
Plug Load	5	Plug Load Power Density (W/m^2)	PLPD	50	D& O
	6	Plug Load Schedule	SCHPL	50	O
Building Envelopes	14	Ext. Walls R-value (W/m^2-K)	REXTWALL	50	D
	20	Ext. Windows R-Value (W/m^2-K)	RWIN	50	D
	21	Ext. Windows SHGC	SHGCWIN	50	D& O
	22	Building Infiltration Rate	INFIL	50	D& O
Zones Temp. Control	25	Zone Cooling Set Points (°C)	SEPTTRMC	-35	O/C
	26	Zone Heating Set Points (°C)	SEPTTRMH	40	O/C
HVAC System	29	Fan Motor Efficiency (%)	SFMEFF	-50	D& O
	31	Fan Part-Load Efficiency Curve	SFPLEFF	15	D& O
	33	Fan operation schedule	SFCNTRL	43	O/C
	35	Economizer Control (Y/N)	ECOMCNTRL	100	D& O
	36	Supply Air Temp. Set Point (°C)	SEPTSAT	67	O
	37	Terminal Box mini. Airflow	SEPMINAFLTB	50	O
	41	Elec. Reheat Coil Efficiency (%)	EFFREHEAT	-25	D& O
	46	DX coil Low Speed rated COP	COPCOOLLSPD	50	D

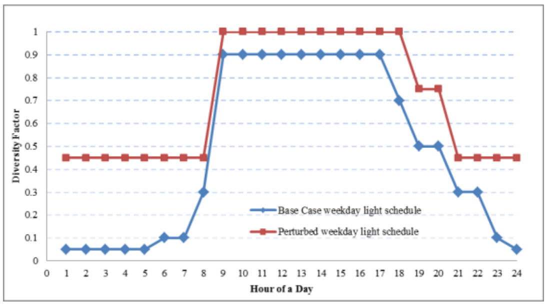

Figure 3*. Step change of weekday interior light schedule*

RESULTS

As listed in Table 2, only the ten most sensitive variables relative to the whole building annual energy consumption are reported in this paper in descending order of calculated sensitivity coefficients. Interior lighting, receptacle load power density, and associated schedules, coded in yellow, appear in almost every location, which indicates interior light and plug loads consume a large fraction of total energy use in this model, with greater relative significance in cooling-dominated climate zones which have internal heat gains which are mostly contributed by lights and plug loads. The room heating and cooling temperature set points, terminal box minimum airflow fraction, and supply fan on/off schedules, shown in green, are the most sensitive control variables for all climate zones. As expected, the zone cooling temperature set point is more sensitive in hot climates and the heating temperature set point plays more important role in cold weather. In addition, cooling and heating equipment efficiencies are identified as relatively more sensitive variables in hot and cold climate, respectively. Figure 4 shows sensitivity coefficients calculated for all variables in three representative cities-Miami (1A), Baltimore (4A), and Fairbanks (8).

Table 2. *Group of ten most sensitive variables*

Miami	Houston	Phoenix	Atlanta	Las Vegas	Los Angeles	San Francisco	Baltimore
PLPD	PLPD	PLPD	SEPTTRMH	SEPTTRMH	PLPD	SEPTTRMH	SEPTTRMH
SCHPL	SCHPL	SCHPL	PLPD	PLPD	SCHPL	PLPD	PLPD
SEPTTRMC	SEPTTRMC	SEPTTRMC	SCHPL	SCHPL	SEPTTRMH	SEPMINAFLTB	SEPMINAFLTB
LPDIL	SEPTTRMH	LPDIL	SEPMINAFLTB	SEPTTRMC	SEPMINAFLTB	SCHPL	SCHPL
SCHIL	LPDIL	SCHIL	SEPTTRMC	LPDIL	SEPTTRMC	LPDIL	LPDIL
COPCOOLLSPD	SCHIL	SEPTTRMH	LPDIL	SEPMINAFLTB	LPDIL	SEPTTRMC	SEPTTRMC
SEPMINAFLTB	SEPMINAFLTB	SEPMINAFLTB	SCHIL	SCHIL	SCHIL	SFCNTRL	SCHIL
SFCNTRL	SFCNTRL	COPCOOLLSPD	SFCNTRL	SFCNTRL	SFCNTRL	SCHIL	SFCNTRL
SHGCWIN	COPCOOLLSPD	SFCNTRL	COPCOOLLSPD	COPCOOLLSPD	COPCOOLLSPD	SHGCWIN	EFFREHEAT
LPDEL	SHGCWIN	SHGCWIN	EFFREHEAT	SHGCWIN	SHGCWIN	RWIN	RWIN
Albuquerque	**Seattle**	**Chicago**	**Boulder**	**Minneapolis**	**Helena**	**Duluth**	**Fairbanks**
SEPTTRMH	SEPTTRMH	SEPTTRMH	SEPTTRMH	SEPTTRMH	SEPTTRMH	SEPTTRMH	SEPTTRMH
PLPD	SEPMINAFLTB	SEPMINAFLTB	SEPMINAFLTB	SEPMINAFLTB	SEPMINAFLTB	EFFREHEAT	EFFREHEAT
SCHPL	PLPD	PLPD	PLPD	EFFREHEAT	PLPD	SEPMINAFLTB	SEPMINAFLTB
SEPMINAFLTB	SCHPL	EFFREHEAT	SCHPL	PLPD	EFFREHEAT	PLPD	RWIN
SEPTTRMC	LPDIL	SCHPL	LPDIL	SCHPL	SCHPL	RWIN	PLPD
LPDIL	SFCNTRL	LPDIL	SEPTTRMC	LPDIL	LPDIL	SCHPL	LPDIL
SCHIL	EFFREHEAT	SEPTTRMC	EFFREHEAT	RWIN	SFCNTRL	LPDIL	SCHPL
SFCNTRL	SEPTTRMC	SFCNTRL	SFCNTRL	SEPTTRMC	SEPTTRMC	SFCNTRL	SFCNTRL
EFFREHEAT	SCHIL	SCHIL	SCHIL	SFCNTRL	RWIN	SEPTTRMC	SCHIL
RWIN	RWIN	RWIN	RWIN	SCHIL	SCHIL	SCHIL	SEPTTRMC

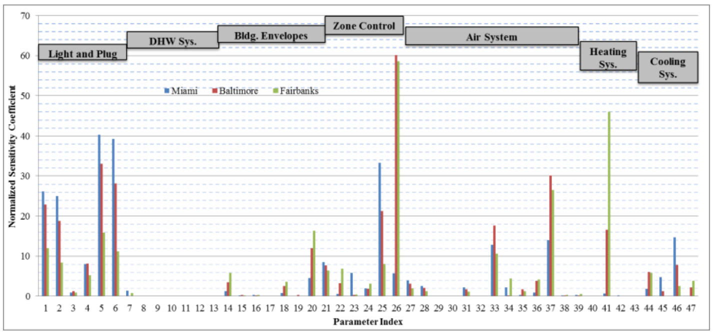

Figure 4. *Building level sensitivity coefficients for Miami, Baltimore, and Fairbanks*

Figure 5 displays sensitivity coefficients for interior lighting systems, fans, cooling and heating systems annual energy use. As expected, the interior lighting energy use is only influenced by interior light power density and its schedules. It also clearly shows that the most sensitive variables to the energy-intensive end users are also most sensitive to the building total energy use compared with the building level sensitivity study results. A group of parameters can also be prioritized and tabled relative to each end user.

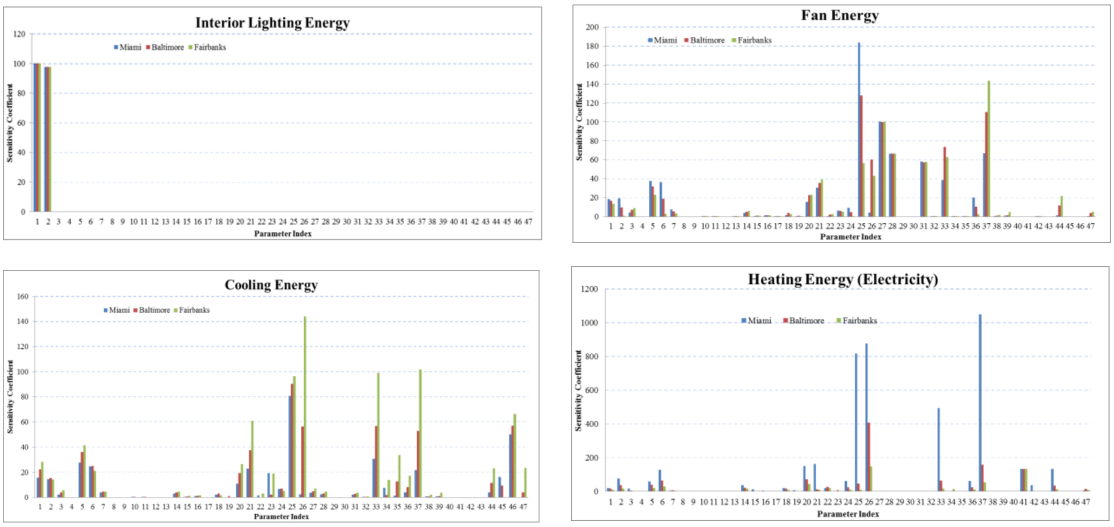

Figure 5. *System level sensitivity coefficients for Miami, Baltimore, and Fairbanks*

DISCUSSION, CONCLUSION AND IMPLICATIONS

The sensitivity study presented in this paper reveals that the annual energy use of a typical commercial medium office building in almost all climate zones is relatively more sensitive to the operational parameters-interior installed lighting and plug load power densities and their schedules, zone heating and cooling temperature set points, terminal box minimum airflow set points and supply fan schedules than other potential model inputs. In hot and humid climate zones, besides the lighting and plug load related parameters and other internal gain contributing factors, such as occupancy density and schedules, the efficiencies of the cooling equipment and window specifications (SHGC, R-value) also have great impact on the annual energy use. On the other hand, in cold climates, the heating equipment efficiency, envelope parameters (R-value of the windows, external walls, and roofs) and infiltrations rates are the relatively more sensitive parameters in determination of energy use. Since the simulation program can easily output annual energy breakdown for different end uses, system level sensitivity coefficients can be calculated and prioritized, as well. The most influential factors to the dominating loads-light and receptacle loads for almost all climate zones, cooling system for hot climates and heating system for cold weather condition, are also the most sensitive variables relative to the whole building energy consumption. The patterns of changes in important parameters with the climate in determining energy use unveiled by this paper are consistent with previous studies. Lam and Hui (1995) conclude that energy use in a typical high-rise office building located in Hong Kong is sensitive to parameters affecting internal loads, window system type, temperature set points and HVAC plant efficiencies. Mottillo (2001) points out that energy use in buildings located in Canada are most sensitive to the characteristics of the building envelope, the installed lighting power density, efficiency of heating equipment, and temperature set point schedules.

The input-output sensitivity analysis technique shown in this paper is created to rank the importance of the numerous inputs of a building energy model. Assumptions are made in order to easily compare the influence of different types of inputs- numeric, schedules, and control strategies. In the first place schedules are aggregated into a single numeric number to account for the effective total hours compared to the base value. For example, the lighting weekday schedule as shown in Figure 3, the sum through 24 hours of base case value is 11.3 hours per day of scheduled lighting. After perturbation, the daily is increased to 16.9 hours, a 50% increase for the weekday schedule. However, the influence of a control strategy change is really difficult to quantify in a normalized way and compare to other numerical inputs. In this investigation, it is assumed the percentage change of inputs affecting control strategies is 100%, but this could lead to underestimating potential control strategy impacts. Finally, the potential minimum value of an input is used to calculate the percentage change of that input, thus the sensitivity coefficient calculated for some variables, such as the supply air temperature set point or a zone heating and cooling temperature set-point could be biased in proportion to the assumed "reasonable" minimum based on the authors' experience. The whole building level and subsystem level sensitivity analysis provides a hierarchical rating to a large number of energy model inputs based on their relative importance to outputs of interest. Given the fact current building energy simulation programs can accurately model building geometries, reconciling an existing commercial office building energy model (similar size and HVAC systems) to its measured energy use become possible if the parameters associated with the most significant sensitivity coefficients can be measured or sub-metered onsite. The prioritized parameter lists generated from the sensitivity study serve as guidance to both energy audit project and new building design, clearly indicating which parameters should be measured and the minimum instrumentation/sub-metering needed for model calibration. It is worth noting that, according to this study, interior lighting and plug load related parameters are important for all climate zones for medium size commercial office buildings, increasing in significance for cooling dominated climate locations. Consequently, sub-metering these end uses is highly recommended in order to well-tune a BEM. Case studies with actual buildings are needed to further validate the sensitive parameters and improve the methodology. The same sensitivity analysis method can also be implemented to other reference building types to generate ranked parameter lists.

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REFERENCES

Anonymity
http://www1.eere.energy.gov/buildings/commercial_initiative/reference_buildings.html, last accessed on 1 July 2012.

Burhenne, S., Jacob, D., & Henze, G. P. (2010). Uncertainty Analysis in Building Simulation with Monte Carlo Techniques. *Fourth National Conference of IBPSA-USA*, (pp. 419-426). New York City.

Carroll, W. L., & Hitchcock, R. J. (1993). Tuning Simulated Building Descriptions to Match Actual Utility Data: Methods and Implementation. *ASHRAE Transactions: Symposia* (pp. 928-934). American Society of Heating, Refrigeration and Air Conditioning Engineering.

Deru, M., Liu, B., Yazdanian, M., Huang, J., & Crawley, D. (2011). *U.S. Department of Energy Commercial Reference Building Models of the National Building Stock.* Golden, Colorado: National Renewable Energy Laboratory.

Eisenhower, B., O'Neil, Z., Fonoberov, V. A., & Mezic, I. (2011). Uncertainty and Sensitivity Decomposition of Building Energy Models. *Journal of Building Performance Simulation*, 1-14.

Haberl, J., & Bou-Saada, T. E. (1998). Procedures for Calibrating Hourly Simulation Models to Measured Building Energy and Environmental Data. *Journal of Solar Energy Engineering*, 193-204.

Kaplan, M., McFerran, J., Jansen, J., & Pratt, R. (1990). Reconciliation of a DOE2.1C Model with Monitored End-Use Data for a Small Office Building. *ASHRAE Transactions*, (pp. 981-992). Atlanta.

Lam, J. C., & Hui, S. C. (1996). Sensitivity Analysis of Energy Performance of Office Buildings. *Building and Environment*, 27-39.

Lee, S. U., & Claridge, D. E. (2002). Automatic Calibration of a Building Energy Simulation Model Using a Global Optimization Program. *Proceedings of the Second International Conference for Enhanced Building Operations.* Richardson, Texas.

Mottillo, M. (2001). Sensitivity Analysis of Energy Simulation by Building Type. *ASHRAE Transactions: Symposia* (pp. 722-732). Amercian Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Norford, L., Socolow, R., Hsieh, E., & Spadaro, G. (1994). Two-to-one discrepancy between measured and predicted performance of a 'low-energy' office building: insights from a reconciliation based on the DOE-2 model. *Energy and Buildings*, 121-131.

Pan, Y., Huang, Z., & Wu, G. (2007). Calibrated Building Energy Simulation and its Application in a High-Rise Commercial Building in Shanghai. *Energy and Buildings*, 651-657.

Petr, K., Filip, J., Karel, K., & Jan, H. (2007). Technique of Uncertainty and Sensitivity Analysis for Sustainable Building Energy Systems Performance Calculations. *Proceedings: Building Simulation*, (pp. 629-636).

Reddy, T. A., Maor, I., & Sun, J. (2006). *Procedures for Reconciling Computer-Calculated Results with Measured Energy Data.* Atlanta, GA: Amercian Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Saltelli, A., Chan, K., & Scott, E. M. (2000). *Sensitivity Analysis.* Chichester: JOHN WILEY & SONS, LTD.

Spitler, J. D., E., F. D., & Zietlow, D. C. (1989). A Primer on the Use of Influence Coefficients in Building Simulation. *Proceedings of Building Simulation Conference* (pp. 299-304). Vancouver: The International Building Performance Simulation Association.