A PRIMER ON THE USE OF INFLUENCE COEFFICIENTS IN BUILDING SIMULATION

by

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ABSTRACT

In order to create a simulation model of a building, it is usually necessary to make a number of assumptions and/or approximations about the building being simulated. Many physical quantities cannot be known precisely when the building is being simulated. For example, the real amount of infiltration is almost never known because it is impossible to predict accurately and difficult to measure. Other examples include quantity and type of internal mass, thermophysical properties of building materials, ground temperatures, and equipment efficiencies.

In addition, occupancy often has a significant, but unpredictable influence on the building energy consumption. Such behavior as opening doors, leaving windows open, changing the thermostat settings, leaving shades open or closed and generating heat due to use of appliances all have an impact on building energy consumption.

In order to gage the accuracy of a simulation, it is necessary to estimate the relevant significance of the assumptions made. By determining which assumptions have significant impact on the building energy consumption, it is possible to determine where effort should be made to refine the simulation. In addition, potential errors can be estimated.

One method of determining the significance of the assumptions made when simulating a building involves the use of influence coefficients. An influence coefficient is the partial derivative of a simulation result with respect to a parameter. An example would be the partial derivative of total building energy consumption with respect to the effective solar transmissivity of a window shade. The simulation result could be any result of interest to the user, such as the total energy consumption, heating or cooling loads, annual energy costs, etc. The parameter could be any assumption that affects the simulation result.

This paper describes the use of influence coefficients to estimate the significance of assumptions made in the building simulation process. A method for calculating and nondimensionalizing influence coefficients is presented. Examples are taken from a study comparing building energy performance of manufactured family housing units to conventionally-built family housing units at Fort Irwin, CA. The building simulation tool is the Building Loads Analysis and System Thermodynamics (BLAST) program. (1)

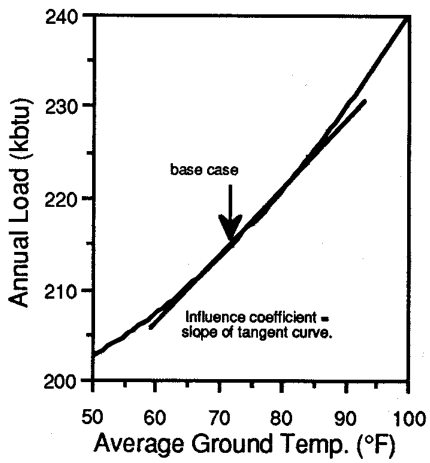
Introduction

Influence coefficients are partial derivatives of one variable with respect to another variable in a system. Influence coefficients quantify the influence of one variable on another. As used in this paper, the influence coefficient indicates the influence of an input parameter on a simulation result, i.e.:

$$\text{Influence Coefficient} = \frac{\partial(\text{Result})}{\partial(\text{Parameter})}$$

An influence coefficient is illustrated in Figure 1. The parameter of interest in this example is the average ground temperature; the result of interest is the annual load (|heating load| + |cooling load|). The load-ground temperature curve was generated by performing eleven annual simulations with different values of average ground temperatures. BLAST allows specification of ground temperatures for each month; the average ground temperature is the average of all twelve values. The influence coefficient is shown as the slope of the tangent to the annual load-ground temperature curve calculated at a design point of interest on the curve--the "base case". The influence coefficient was calculated using the base case simulation and a simulation with average ground temperatures slightly different than the base case average ground temperatures.

Fig. 1 Dimensional Influence Coefficients



In particular, we are interested in the effect that various parameters have on particular simulation results. This effect, quantified as an influence coefficient, can be useful in determining the relative importance of a set of assumptions to a simulation. Influence coefficients can also be used to estimate errors in simulation results. The relative importance of assumptions can be evaluated using either the magnitude of the influence coefficients or the magnitude of the estimated errors.

Influence coefficients may also be useful in identifying important characteristics, such as the dominant driving forces in a building. The relative dominance of the envelope or internal loads may be estimated by calculating influence coefficients for the appropriate parameters. The authors have performed some research in this area, with mixed results.

Influence coefficients are being used in many engineering fields, including vibration (2), optimization (3), gas dynamics (4), and refrigeration(5). See Table 1 for a summary.

For simple systems, influence coefficients can be determined analytically. For complex systems, influence coefficients must be determined numerically. Clearly, buildings fit into the latter category.

Table 1 Examples of Influence Coefficients in other Engineering Fields

Field (Reference)	Influence Coefficient
Vibration(2)	$\frac{\partial(\text{vibration})}{\partial(\text{balancing weight})}$
Optimization (3)	$\frac{\partial(\text{output})}{\partial(\text{result})}$
Gas Dynamics(4)	$\frac{\partial(\text{Mach number})}{\partial(\text{area})}$
Refrigeration (5)	$\frac{\partial(\text{chiller capacity})}{\partial(\text{parameter})}$

Methodology

Numerical calculation of influence coefficients is performed using the standard numerical approximation for a partial derivative:

$$\frac{\partial(\text{Result})}{\partial(\text{Parameter})} \approx \frac{\Delta(\text{Result})}{\Delta(\text{Parameter})}$$

In other words, the parameter of interest is perturbed (from the base case) and the change in the result is divided by the change in the parameter.

Specifically, the method used to determine influence coefficients in this paper is as follows:

1. Simulate the base case building.
2. Identify the parameter and the result of interest.
3. Modify the input file by changing the parameter of interest by an appropriate amount. The change in the parameter should be large enough to cause a numerically significant change in the result.

4. Divide change in result by change in parameter to obtain a dimensional influence coefficient.

5. Non-dimensionalize the influence coefficient as required by the analysis. Techniques for non-dimensionalizing influence coefficients will be discussed later.

Influence Coefficient Forms

There are at least 4 different forms of influence coefficients:

1. *Dimensional.* A dimensional influence coefficient is obtained when the parameter and result do not have the same units. (i.e. $\frac{\partial(\text{Annual Heating Load})}{\partial(\text{Average Ground Temperature})}$ has the units (BTU / ° F).

2. *Non-dimensional type 1.* This type of influence coefficient is obtained when the parameter and the result do have the same units. (i.e. $\frac{\partial(\text{Cooling Load})}{\partial(\text{Internal Heat Gain})}$ has the units (BTU / BTU).

3. *Non-dimensional type 2.* A dimensional influence coefficient can be transformed into a non-dimensional influence coefficient by non-dimensionalizing the parameter and the result. One way is to divide the parameter by its base case value and divide the result by its base case value.

$$\frac{\partial(R^*)}{\partial(P^*)} \approx \frac{\Delta R^*}{\Delta P^*}$$

where

$$\Delta R^* = R^*_{bc} - R^*_{\Delta} = \frac{R_{bc}}{R_{bc}} - \frac{R_{\Delta}}{R_{bc}}$$

$$\Delta P^* = P^*_{bc} - P^*_{\Delta} = \frac{P_{bc}}{P_{bc}} - \frac{P_{\Delta}}{P_{bc}}$$

P = Parameter
R = Result
* = non-dimensionality
bc = base-case
Δ = value for perturbed case.

4. *Dimensional type 2.* This type of influence coefficient is similar to the non-dimensional type 2, except that only the numerator is non-dimensionalized.

$$\frac{\partial(R^*)}{\partial(P)} \approx \frac{\Delta R^*}{\Delta P}$$

Significance of Assumptions and Error Analysis

Determining the significance of various assumptions is a problem that concerns most users of building simulation programs. The approach presented here is to use influence coefficients to determine the relative importance of various assumptions by estimating the potential errors involved with each assumption. The assumptions with the highest potential errors are the ones that the user need be most concerned about refining. In some cases, further refinement of an assumption may be impossible. However, performing an error analysis will give the user some idea of the limits of accuracy of the simulation.

One convenient way of performing an error analysis is to compute influence coefficients in the dimensional type 2 form. The influence coefficients can be multiplied by the estimated parameter error to give the estimated error in the result.

Influence coefficients may be calculated on the basis of any number of simulation results. The result chosen for a given simulation depends on the application. For example, if the purpose of the energy analysis is to determine if the building meets prescribed energy budgets, then annual energy loads or consumption would be the appropriate result for calculating an influence coefficient. If, however, minimizing life cycle costs is the objective of the simulation, then annual energy costs would be the desired result for calculating an influence coefficient. If the objective is to optimize the building design with respect to energy consumption, influence coefficients should be calculated on the basis of the building energy load rather than on the basis of energy consumption or cost. The energy load is the amount of heating and cooling required by the building. This result, since it does not include system inefficiencies, shows most clearly the relative importance of non-system design parameters. (e.g. ground temperature, infiltration, internal mass, etc.)

Purposeful selection of the result used in the calculation of the influence coefficient is a prerequisite to obtaining a meaningful assessment of the assumptions made in the simulation. In the following example influence coefficients are calculated on the basis of annual loads (for the purpose of design optimization), and on the basis of annual cost (for the purpose of minimizing life cycle costs). The relative significance of the simulation assumptions, as shown by the results of the error analysis, are different for the two cases.

Example

This example is taken from a comparative study of light frame construction family housing units at Ft. Irwin, California, (6). The study compared two types of buildings, one "factory" built and one "conventionally" built.

Both of the buildings were four unit, two story apartment buildings with several significant design differences. The factory built unit (FBU) consisted of prefabricated walls which were assembled on a crawlspace at the building site. The conventionally built unit (CBU) was constructed entirely at the building site on a concrete slab. The FBU was designed with approximately twice the window area of the CBU. In addition the FBU windows were of single pane construction while the CBU windows were of double pane construction.

Both buildings were modeled for the study using the BLAST hourly energy analysis program. The annual simulations were performed for a hot desert climate with approximately twice as many annual cooling degree days as heating degree days.

Five parameters were selected as potentially having a significant impact on building performance. Assumptions were made to determine the magnitude of each of these parameters for the simulations. The parameters, shown in Tables 2a and 2b, were "perturbed" in successive BLAST runs of the buildings. Dimensional type 2 influence coefficients were then calculated for each parameter. Appendix A contains a complete sample calculation for one parameter.

In order to compare both the buildings and the sets of influence coefficients based on different simulation results, the influence coefficients were calculated on the basis of the total annual energy load (|heating| + |cooling|) and on the basis of the annual energy cost for both the CBU and the FBU. Additional information could be obtained by calculating two sets of influence coefficients for each parameter, one based upon the annual heating load and one based upon the annual cooling load.

The influence coefficients shown in Tables 2 and 3 span six orders of magnitude. They can't be directly compared with one another, since the units for each are different. In order to make a direct comparison, the estimated error in the result due to error in each parameter must be calculated. The error in the result is calculated from the dimensional type 2 influence coefficient as follows:

$$|\text{Error in result}| = \frac{\Delta R^*}{\Delta P} \times |\text{Est. parameter error}|$$

The design differences between the FBU and the CBU are evident from both the cost based and the load based error analyses (Tables 2a, 2b, 3). The ground temperature had a significant effect on the conventionally built unit since this unit was constructed on a concrete slab. The factory built unit, constructed on a crawlspace was not particularly sensitive to ground temperature perturbations. Shading from blinds was more significant in the FBU with its greater window area.

The cost based and the load based influence coefficients for the CBU are compared in Figure 2. The influence coefficients were calculated from identical parameter perturbations but based on different simulation results. Using energy (total loads) based influence coefficients, infiltration was the most significant parameter followed by ground temperature and internal loads. Using cost based influence coefficients, internal loads was the most significant parameter followed by ground temperature and infiltration. The order of significance changes due to the relative costs of heating and cooling. (Costs used for cost-based errors: \$0.10/kwh for electricity; \$0.50/therm for gas.)

Limitations

The method described in this paper does have some limitations:

1. Not all uncertainties and assumptions may be reduced to the single parameter required for the calculation of an influence coefficient.

2. The effects of some parameters may be so non-linear that the influence coefficient cannot yield a reasonable estimate of the

Table 2a Influence Coefficients and Error Analysis for Conventionally-built Units

Simulation Parameter	Base-case Value	Dimensional I.C. Type 2	Est. Error (Parameter)	Est. Error (Result)
Avg. Ground temp.	75 °F	0.00374 $°F^{-1}$	10 °F	±3.7 %
Outside air infiltration	1204 cfm	0.000165 cfm^{-1}	500 cfm	±8.3 %
Internal mass (area)	8876 ft^2	5.2×10^{-7} ft^{-2}	2000 ft^2	±0.1 %
Internal loads (annual)	73,951 kbtu	1.62×10^{-6} $kbtu^{-1}$	20,000 kbtu	±3.2 %
Trans. of blinds	0.5	.0597	0.2	±1.2 %

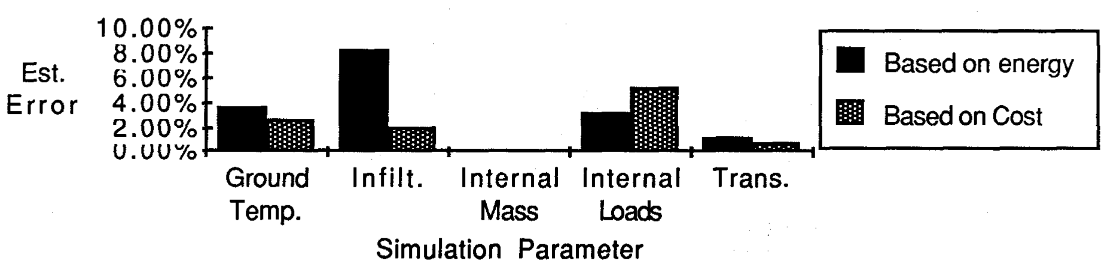
Table 2b Influence Coefficients and Error Analysis for Factory-built Units

Simulation Parameter	Base-case Value	Dimensional I.C. Type 2	Est. Error (Parameter)	Est. Error (Result)
Avg. Ground temp.	75 °F	0.00063 $°F^{-1}$	10 °F	±0.6 %
Outside air infiltration	1084 cfm	0.000176 cfm^{-1}	500 cfm	±8.8 %
Internal mass (area)	9664 ft^2	1.2×10^{-6} ft^{-2}	2000 ft^2	±0.2 %
Internal loads (annual)	73,951 kbtu	1.16×10^{-6} $kbtu^{-1}$	20,000 kbtu	±2.3 %
Trans. of blinds	0.5	.166	0.2	±3.3 %

Table 3 Influence Coefficients and Error Analysis Based on Cost

	Factory Built Units		Conventionally Built Units	
Simulation Parameter	Dimensional I.C. Type 2	Est. Error (Result)	Dimensional I.C. Type 2	Est. Error (Result)
Avg. Ground temp.	5.66×10^{-4} $°F^{-1}$	±0.6 %	2.66×10^{-3} $°F^{-1}$	±2.7 %
Outside air infiltration	$6.4 1 \times 10^{-5}$ cfm^{-1}	±3.2 %	4.12×10^{-5} cfm^{-1}	±2.1 %
Internal mass (area)	$8.06 \times 10^{--7}$ ft^{-2}	±0.2 %	-1.71×10^{-7} ft^{-2}	± 0.0 %
Internal loads (annual)	2.08×10^{-6} $kbtu^{-1}$	±4.2 %	2.71×10^{-6} $kbtu^{-1}$	±5.4 %
Trans. of blinds	0.115	±2.3 %	0.0378	±0.8 %

Fig. 2 Influence Coefficients Based on Energy and Cost



error in the result. The authors have not yet encountered any parameters with a high degree of non-linearity.

3. The accuracy of the influence coefficients is limited by the accuracy of the simulation. As an example, a simulation program with a poor model of ground heat transfer may yield influence coefficients that accurately reflect the effects of ground temperature on the simulation, but not on the actual problem.

4. At this point in time, calculation of influence coefficients requires a moderate amount of effort on the user's part. In the future, this calculation could be automated and added to simulation programs.

5. Finally, this is not a "cookbook" method. Good engineering judgment is required to know what influence coefficients to evaluate and to be able to estimate the potential error in the parameters so that error in the results can be correctly estimated.

Conclusions

This paper has presented a powerful method for evaluating the significance of the assumptions made in building simulation programs. At present, error analysis by the influence coefficient method requires a reasonable, yet not insignificant, effort on the part of the user. Implementing the capability to calculate influence coefficients in an hourly energy analysis program such as BLAST would allow the program user to easily and quickly estimate the error in results and evaluate the significance of assumptions.

Additional research is required in order to investigate other possible uses of influence coefficients, such as classifying buildings.

Appendix A

Sample Calculation

This sample calculation illustrates how the numbers in Table 2b were determined for the average ground temperature.

1. From the base case simulation output file, record the average annual ground temperature(P_{bc}=75°F) and the heating(49.4 kbtu) and cooling (230.1 kbtu) loads.

2. Calculate the total load by summing the magnitude of the heating and cooling loads (R_{bc}=49.42+230.1=279.52 kbtu).

3. "Perturb" the ground temperature by changing the ground temperature parameter in the BLAST input file by 3°F(P_Δ=78°F) and run another simulation.

4. From the perturbed simulation record the heating(49.05 kbtu) and cooling (231. kbtu) loads.

5. Calculate the total load by summing the magnitude of the annual heating and cooling loads (R_Δ=280.05 kbtu).

6. Calculate the type 2 dimensional i.c.

$$\frac{\frac{R_{bc}-R_\Delta}{R_{bc}}}{P_{bc}-P_\Delta} = \frac{\frac{279.52-280.05}{279.52}}{75-78} = .000632\ °F^{-1}$$

7. Estimate error in the parameter (± 10°F).

8. Calculate the percent error in the result.

percent error=type 2 dimensional i.c. x error in parameter x 100

percent error=.000632 x 10 x 100=0.632

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