Commercial Building/System Characteristics Sensitivity Analysis

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A Pacific Northwest utility is conducting a project to develop an accurate and affordable savings verification methodology for new commercial buildings in one of their demand-side management (DSM) incentive programs. The methodology involves the development of an as-built model of building energy performance using the DOE-2 simulation. To cost effectively acquire the information necessary for DOE-2 to accurately simulate building performance, it is important to understand the sensitivity of model results to variations in characteristic input values. With this understanding, efforts can focus on obtaining good values for those variables identified as having a significant impact on the results.

This paper discusses the results of a sensitivity analysis performed to identify the relative importance of several building and system characteristics required as input to the DOE-2.ID model. Two prototype commercial buildings, a 26,000 square foot grocery and a 34,000 square foot office building, were selected for the study using Portland, Oregon weather.

For each building, 17 variables were identified for study. These variables not only have potential for significant impact, but may also be somewhat uncertain without a costly measurement and/or audit effort. The DOE-2 simulation was run with high and low values over a reasonable range for each variable. The results of the analysis are presented as percent changes in total building energy consumption from an established baseline.

Introduction

A Northwest electric utility is conducting a project to develop an accurate and affordable savings verification methodology for new commercial buildings participating in their demand-side management (DSM) program. The methodology involves the development of an as-built model of building energy performance using the DOE-2 simulation. To cost effectively acquire the information necessary for DOE-2 to accurately simulate building performance, it is important to understand the sensitivity of model results to variations in characteristic input values.

The objective of this sensitivity analysis was to characterize the importance of various commercial building and HVAC system characteristics to the results of building energy simulations. This will assist modelers in determining where to focus their efforts when gathering characteristic information on buildings to be modeled for this Northwest utility's DSM program savings verification. These findings are specific to the DOE2.1D simulation program for buildings in a climate comparable to that of Portland, Oregon.

Methodology

To perform this analysis prototypical baseline DOE2.lD models for a 26,000 square foot (sf) grocery and a 34,000 sf office building were developed. These two building types represent significant shares within the utility's incentive program. These baseline models were to be representative of new all-electric buildings constructed in the utility's service territory. Table 1 presents the annual electric energy use and shares by end use for each of the buildings under long-term average Portland, Oregon weather conditions.

The principal characteristics of the two buildings were based upon prototypes developed for an earlier project (SBW, 1990) to evaluate the impact of revisions to the

Table 1. Baseline Annual End Use Consumption

26,000 sf GROCERY

End Use	kWh/sf	%
Space Heat	0.7	1.0%
Space Cool	0.4	0.5%
HVAC Aux.	5.1	7.3%
Hot Water	0.3	0.4%
Lighting	14.1	20.0%
Misc. Equip.	4.7	6.6%
Refrigeration	45.1	64.1%
Total	70.4	

34,000 sf OFFICE

End Use	kWh/sf	%
Space Heat	5.4	26.9%
Space Cool	1.4	7.0%
HVAC Aux.	2.0	9.7%
Hot Water	0.1	0.5%
Lighting	7.4	36.6%
Elevator	0.3	1.6%
Misc. Equip.	3.6	17.9%
Total	20.1	

Model Conservation Standards (MCS). These prototypes represented current (1989) new construction practices in the Pacific Northwest. They were developed from discussions with building designers, builders, building code officials, and building operations and construction managers. Characteristic and end-use load data from the End-Use Load and Consumer Assessment Project (ELCAP) were also used to develop the prototype building models.

The office is a 2-story structure cooled by two chillers and heated by electric resistance. A variable air volume air distribution system is used throughout the building, with the terminals in the perimeter zones being parallel induction units which pull heat from the core zones. The building was divided into 10 zones, a core and four perimeter zones for each floor, for simulation purposes.

The grocery is a modern full-service store. Heat is reclaimed from the food refrigeration condensers to provide space heating in the main sales area. The refrigeration system uses air-cooled condensers and the head pressure is allowed to float down to a minimum condensing temperature of 80 F. The store was divided into two zones, the main sales area and a back storage area. The ability to model supermarket refrigerated case work was incorporated into Version D of the DOE2.1 simulation (LBL, 1989). For this study, the grocery's refrigerated case work was divided into two systems, low and medium temperature, for each of the two building zones.

After establishing the two prototype building models, lists were then developed of major DOE-2.1D input variables for each building. Fifty-nine variables were identified for the grocery and 43 variables were identified for the office building. Based upon the relative importance of the different end uses and our modeling experience, we then selected 17 variables for each building whose values could potentially have a significant impact on the total building's electric energy use.

We then assigned values at the high and low end of a reasonable range for each variable. An input variable will be considered sensitive if it impacts the total building's electric energy use by more than 5% when it is varied over its reasonable range of values. Our level of understanding of the reasonable range for each of the variables of interest could have an impact on the sensitivity results.

DOE-2 simulations were performed with the high and low values for each of the selected variables. In some cases, the typical value used in our baseline model may have been at or near one of the extremes.

Results

The results of the DOE-2 simulation runs for the all-electric grocery are presented in Table 2. The building's total energy use for each simulation is presented as kWh/sf and the percent change from the baseline value.

In the grocery, anything that affects refrigeration loads has a significant impact because refrigeration represents 64% of the building total. Building envelope values have little impact because heating/cooling loads only represent 1.5% of the building total. Cooling loads are minimal in the Northwest climate and heat is being reclaimed from the refrigeration condenser system for space heating.

Refrigeration auxiliaries include anticondensate heaters, lights, and evaporator fans in the refrigerated case work. The DOE-2 simulation not only accounts for the energy use of the auxiliaries, but also adds their associated heat input to the refrigerated case load. Thus, the refrigeration auxiliaries input variable has a double impact, the energy use of the auxiliary load as well as the additional refrigeration compressor energy to meet the added case load. The appropriateness of adding all of the auxiliary heat to the case load is beyond the scope of this study. The point to be made here is that the simulation results

Table 2. Grocery Sensitivity Analysis Results

Variable (baseline value)	Variable Range	Total Bldg. Energy (kWh/sf)	Change %
Roof Insulation (R19)	R11	70.45	0.1
	R38	70.29	-0.1
Infiltration Rate (0.25 ACH)	1.0	71.84	2.1
Lighting Capacity (1.8 W/sf)	1.1	65.80	-6.5
	2.3	73.66	4.7
Lighting Schedule (0.65/0.95)	0.05/0.95	67.64	-3.9
	0.95/0.95	71.78	2.0
Equipment Capacity (4.5 W/sf)	2.0	67.82	-3.6
	10.0	75.94	7.9
Heat Reclaim to DHW (yes)	no	74.27	5.6
Operating Hours (168)	112	61.87	-12.1
Heating Setpoint Temp. (70 heat/72 cool)	68/72	69.50	-1.2
	74/76	71.23	1.2
Minimum Outside Air Fraction (0.15)	0.05	70.10	-0.4
	0.30	71.27	1.3
Exhaust Air Flow (0 cfm/sf)	0.15	71.35	1.4
Ref. Zone Load (3.3 low/9.9 med. Btu/sf)	1.6/5.0	61.81	-12.1
	5.0/15.0	79.40	12.9
Ref. Aux. Capacity (1.4 low/0.6 med. W/sf)	0.7/0.3	56.01	-20.4
	2.5/1.2	94.56	34.4
Ref. Auxiliary Schedule (1.0 night/1.0 day)	0.35/0.75	60.05	-14.6
Defrost Type (hot gas)	electric	78.34	11.4
Minimum Condensing Temperature (80)	70	68.95	-2.0
	120	80.92	15.0
Heat Reclaim (yes)	no	81.01	15.2
Heat Reclaim Temperature (110)	90	67.98	-3.4
	140	75.07	6.7

can be very sensitive to the value of the refrigeration auxiliaries input and modelers should quantify its value carefully.

Varying the heat reclaim temperature input variable (REFG-TREC-T) sets the minimum condensing temperature of the refrigeration system when heat is being reclaimed for space heating purposes. Thus, its effect on the refrigeration system energy use is similar to varying the minimum condensing temperature (REFG-MIN-COND-T).

The building heating load shown represents the unit heaters in the back storage area zone. Reclaim heat is meeting all of the sales area heating requirements. Thus, changing the thermostat setpoints in the sales area impacts the heating requirements of the building in a manner opposite to what would be expected. Raising the heating setpoint in the sales area lowers the heating requirement in the storage area due to the greater conduction of heat from the sales area zone to the storage area zone. Conversely, lowering the sales area setpoint results in an increased storage area heating requirement.

The results for the office building are shown in Table 3. Lighting measures significantly affect heating requirements. With heating energy representing 27% of the building total, envelope values have a more significant impact. The results are very sensitive to the minimum box

Table 3. Office Sensitivity Analysis Results (All Electric)

Variable (baseline value)	Variable Range	Total Bldg. Energy (kWh/sf)	Change %
Roof Insulation (R19)	R11	20.48	1.7
	R38	19.92	-1.1
Wall Insulation (R11)	R5	20.61	2.3
	R19	19.72	-2.1
Window U-value (0.55)	0.35	19.44	-3.4
	0.9	21.31	5.8
Glass Shading Coeff. (0.5)	0.3	20.69	2.8
	0.88	19.30	-4.1
Glass Facing Direction (south)	north	20.08	-0.3
	west	20.12	-0.1
Window Area % of Wall (20)	10	20.05	-0.4
	40	20.50	1.8
Infiltration Rate (0.3 ACH)	0.15	19.91	-1.1
	0.55	20.54	2.0
Lighting Capacity (1.75 W/sf)	1.1	18.79	-6.7
	2.3	21.33	5.9
Lighting Schedule (0.10/0.85)	0.05/0.65	19.16	-4.9
	0.30/0.95	21.66	7.6
Equipment Capacity (3.0 W/sf)	1.0	18.60	-7.6
	5.0	21.72	7.9
Operating Hours/Week (63)	45	18.32	-9.0
	85	21.39	6.2
Heating Setpoint Temp. (72 heat/75 cool)	68/75	18.05	-10.4
	74/78	22.01	9.3
Heating Setback (10)	0	20.32	0.9
	15	20.09	-0.2
Economizer (yes)	no	21.58	7.2
Minimum Outside Air Fraction (0.10)	0.05	20.11	-0.1
	0.25	20.52	1.9
Minimum Box CFM Ratio (0.5 perimeter/0.1 interior)	0.1/0.1	15.34	-23.8
	0.5/0.7	17.31	-14.0
	0.7/0.7	18.87	-6.3

cfm ratio and its impacts on heating and cooling loads. Some of this is due to interaction with the supply air reset control.

Tables 4 and 5 list the variables studied in order from most sensitive to least sensitive. The impact percentage reflects the percentage change in total building energy use over the potential range of the variable. In other words, the total building electric energy use with the high value for the input variable is the stated percentage higher than the total energy use with the low value for the input variable. The line separates those variables which are considered to be sensitive because they impact the total building energy use by more than 5%.

Table 4 indicates that 12 variables have sensitivities greater than 5% in the grocery. Five of these variables are directly related to the energy use of the refrigeration

Table 4. % Impact on Total Building Electric Consumption; Characteristic Variable Ranking, Grocery (All Electric)

Input Variable	% Impact (High to Low)
Ref. Aux. Capacity	68.8%
Ref. Zone Load	28.5%
Minimum Condensing Temp.	17.4%
Ref. Auxiliary Schedule	17.2%
Heat Reclaim	15.2%
Operating Hours	13.7%
Equipment Capacity	12.0%
Lighting Capacity	11.9%
Defrost Type	11.4%
Heat Reclaim Temperature	10.4%
Lighting Schedule	6.1%
Heat Reclaim to DHW	5.6%
Heating Setpoint Temp.	2.5%
Infiltration Rate	2.1%
Min. Outside Air Fraction	1.7%
Exhaust Air Flow	1.4%
Roof Insulation	0.2%
Defrost Control	0.0%

Table 5. % Impact on Total Building Electric Consumption; Characteristic Variable Ranking, Office (All Electric)

Input Variable	% Impact (High to Low)
Minimum Box CFM Ratio	31.3%
Heating Setpoint Temp.	21.9%
Equipment Capacity	16.8%
Operating Hours/Week	16.8%
Lighting Capacity	13.5%
Lighting Schedule	13.0%
Window U-value	9.6%
Glass Shading Coefficient	7.2%
Economizer	7.1%
Wall Insulation	4.5%
Infiltration Rate	3.2%
Roof Insulation	2.8%
Window Area % of Wall	2.2%
Min. Outside Air Fraction	2.0%
Heating Setback	1.1%
Glass Facing Direction	0.3%

systems. Three other variables are related to heat reclaim which indirectly affects refrigeration energy use by affecting the condensing temperature. Operating hours, internal equipment and lighting are the other important variables in the grocery.

Table 5 indicates that the office building has 9 variables with sensitivities greater than 5%. The high sensitivities of the minimum box CFM ratio and the heating setpoint temperature are specific to a variable air volume HVAC system. The other sensitive variables are primarily related to internal lighting and equipment loads and solar gain.

The variable ranking presented in Tables 4 and 5 only apply to a grocery with a very small heating load because condenser heat is being reclaimed and an office building with electric space heat. To examine the impact of space heating fuel type, the office model was changed to use a gas-fired hot water boiler for space heating.

Because the end uses other than heating are essentially unchanged, the sensitivity of the same variables in an office building with gas space heating can be approximated by simply removing the space heating impact. This results in a baseline total building electricity use of 14.73 kWh/sf. Table 6 presents the impact on the building's total electric energy use for all of the variables in the gas heated office building.

Table 7 presents the variables in order of sensitivity. The order of variables has changed slightly with the Minimum Box CFM Ratio and Heating Setpoint variables dropping in importance. Also the number of sensitive variables with an impact percentage greater than 5% has decreased. The heating setpoint temperature, window u-value, and glass shading coefficient are no longer sensitive variables.

Other Sensitivity Study Results

The results of a similar study of modeling input sensitivity by Corson (Corson, 1990) examined 25 variables for a small (5088 sf) retail building in the Pacific Northwest. Based upon the results of DOE 2.1 modeling, only 8 of the 25 inputs caused a 5 percent or greater change in energy usage. These 8 variables were 1) changing the heat source from resistance to a heat pump (-25.1%), 2) going from a 4-pipe single zone, no economizer system to a dual deck multizone system with an economizer and outside air temperature reset (+22.9%), 3) changing wall insulation

Table 6. Office Sensitivity Analysis Results (Gas Space Heat)

Variable (baseline value)	Variable Range	Total Bldg. Electric (kWh/sf)	Change %
Roof Insulation (R19)	R11	14.71	-0.1
	R38	14.74	0.1
Wall Insulation (R11)	R5	14.75	0.2
	R19	14.72	-0.0
Window U-value (0.55)	0.35	14.72	-0.1
	0.9	14.78	0.3
Glass Shading Coeff. (0.5)	0.3	14.75	0.2
	0.88	14.74	0.1
Glass Facing Direction (south)	north	14.73	-0.0
	west	14.73	-0.0
Window Area % of Wall (20)	10	14.75	0.1
	40	14.76	0.2
Infiltration Rate (0.3 ACH)	0.15	14.72	-0.0
	0.55	14.74	0.1
Lighting Capacity (1.75 W/sf)	1.1	12.28	-16.6
	2.3	16.79	14.0
Lighting Schedule (0.10/0.85)	0.05/0.65	12.99	-11.8
	0.30/0.95	17.11	16.2
Equipment Capacity (3.0 W/sf)	1.0	12.21	-17.1
	5.0	17.24	17.0
Operating Hours/Week (63)	45	13.27	-9.9
	85	15.79	7.2
Heating Setpoint Temp. (72 heat/75 cool)	68/75	14.60	-0.9
	74/78	14.75	0.1
Heating Setback (10)	0	14.75	0.1
	15	14.72	-0.0
Economizer (yes)	no	16.82	14.2
Minimum Outside Air Fraction (0.10)	0.05	14.69	-0.2
	0.25	14.85	0.8
Minimum Box CFM Ratio (0.5 perimeter/0.1 interior)	0.1/0.1	13.97	-5.2
	0.5/0.7	14.21	-3.5
	0.7/0.7	14.53	-1.4

from R-2 to R-13 (-21.9%), 4) adding 2 hours per day to the occupied schedule (+16.5%), 5) adding 50% more peak cooling capacity (+15.1%), 6) increasing heating set point by 5 degrees (+14.7%), 7) operating the supply air fan during unoccupied hours (+11.8%), and 8) reducing lighting power by 30% (-5.0%).

Another sensitivity study by Jacobs (Jacobs, 1994) of a 20,000 sf office building in Denver also concluded that important input variables included lighting and equipment schedules, window properties and shading, and HVAC system operating schedules and control strategies.

Conclusions

This sensitivity analysis of characteristic variables for a grocery and an office building suggests that, under any heating scenario, lighting and equipment capacities be carefully considered when modeling. All inputs affecting the refrigeration load in the grocery are important because

Table 7. % Impact on Total Building Electric Consumption; Characteristic Variable Ranking, Office (Gas Space Heat)

Input Variable	% Impact (High to Low)
Equipment Capacity	41.2%
Lighting Capacity	36.7%
Lighting Schedule	31.7%
Operating Hours/Week	19.0%
Economizer	14.2%
Minimum Box CFM Ratio	5.4%
Min. Outside Air Fraction	1.1%
Window U-value	0.4%
Heating Setpoint Temp.	0.2%
Wall Insulation	0.2%
Roof Insulation	0.2%
Window Area % of Wall	0.2%
Heating Setback	0.2%
Glass Shading Coeff.	0.1%
Infiltration Rate	0.1%
Glass Facing Direction	0.0%

of the significance of that load. When modeling an office building with fossil fuel heating, efforts can focus almost entirely on the lighting and equipment loads and whether or not an economizer is employed.

The applicability of these findings to other building types and locations is limited. Other building types, as well as atypical groceries and office buildings, with different end use characteristics and potentially different HVAC system types could respond quite differently to variations in the same variables.

The sensitivity results for the office building or the grocery can be applied to larger and smaller buildings of the same type within the same climate. Envelope measures would only become important at building sizes below the utility's DSM program limit of 12,000 square feet. Internal loads dominate in larger buildings which is consistent with the two prototype buildings studied. The HVAC system type may change in a larger office building which may impact the sensitivity of variables specific to the HVAC system type.

The magnitude of the impact of weather conditions on the sensitivity analysis results is uncertain. Under more severe climate conditions, insulation levels would become more important but by how much is unknown. Outdoor temperatures also directly impact economizer operation and refrigeration system condensing temperature, two variables which are already sensitive. Investigating the impact of other climate conditions was beyond the scope of this study .

How Utility Program Managers and Evaluators Can Use the Results

Using sophisticated energy simulation models can be difficult due to the large number of variables and the lack of real information on what their values should be. It is much too expensive for field monitoring, audits, and measurement to establish proper values for every modeling input. To reduce program cost but maintain accuracy, it is useful to know in advance which of the many variables has a large impact on the energy usage estimate. For a retrofit program in existing buildings, only the critical inputs need to be measured by the audit. Non-critical inputs can be estimated within the range of reasonable values with no loss of accuracy. Gathering less audit data will reduce the time and cost.

For a new commercial building program, the sensitive variables must be considered carefully by the energy modelers. During the energy savings verification process the critical variables warrant field verification while non-critical variables should remain as estimates. At this Northwest electric utility new work is underway to identify critical variables in additional building types. There is also work beginning to establish better field measurement techniques for critical variables.

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