A SIMPLIFIED ENGINEERING SIMULATION TOOL FOR CALIBRATION TO MONTHLY ENERGY

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ABSTRACT

Conventional simulation tools used during design studies are not well adapted for a post-hoc study since these tools are not designed for easy calibration to actual weather and consumption. Given that consumption data are most readily available as monthly records, the complications of an hourly model are not necessary and can be avoided. A spreadsheet tool has been developed that is a simplified simulation model designed to match actual weather and monthly utility bills. This tool can operate with only simple information about the facility, yet provides a specific options for the HVAC system and equipment. The methodology explicitly allows for specification of HVAC control options that are difficult in other simulation models. Thus, it is a quick approach to treating the facility as an integrated whole and is most useful for existing facilities where utility billing records exist.

INTRODUCTION

Building simulations are usually developed as hourly models (e.g. DOE2, Energy Plus). This is logical during the design process because these tools are frequently used to assess the various equipment configurations under dynamic conditions. However, less elaborate modeling is still adequate to assess many operational decisions. Furthermore, when calibrating a simulation model to match utility consumption records, it may be that only monthly consumption records are available. If so, the hourly model produces output that cannot be confirmed with available data and thus fails to justify the complexity and expense of developing the high-resolution model. Hourly simulations certainly have their place as design tools. However, there is little value in producing calculations to a level of detail that can neither be confirmed nor denied with the available data.

This paper discusses an alternative approach to simulation based on a monthly methodology. Instead of going through all the computations of computing thermal loads by hour, the modeling tool computes the thermal loads on a monthly basis. Since the utility bills provide only monthly data for comparison, there is no point in more laborious computations. This simplifying detail allows the model to be implemented in a standard spreadsheet.

METHODOLOGY

The simplified simulation tool operates in an analogous manner to other simulation tools. First, a thermal simulation computes the required heating and cooling thermal energy. Then, a model of the physical plant computes the amount of purchased energy required to meet the thermal loads.

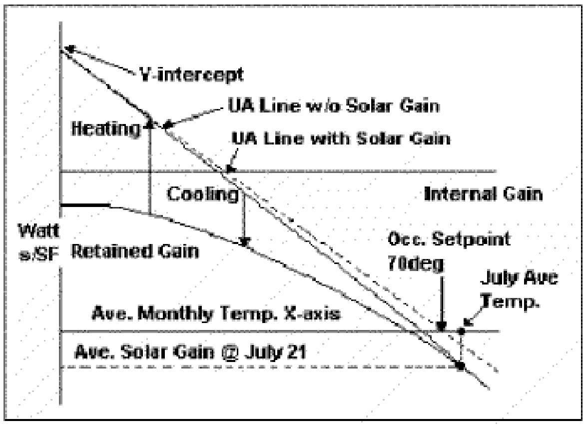

Figure 1. Method to DisaggfregateTthermal Loads

The first computation of thermal loads may be novel to modeling practioners because they are familiar with the complexity of modeling dynamic building interactions. Obviously, both heating and cooling can occur at the same time in different zones of the building. However, it has been demonstrated that the aggregate, monthly performance of buildings can be quite well defined (White and Reichmuth, 1996). In effect, the dynamic variations smooth out when aggregated over time. Applying the method of White and Reichmuth results in an algorithm that computes both heating and cooling thermal loads on a monthly basis.

Figure 1 illustrates the method of White and Reichmuth. The results from detailed hourly simulations have been shown to follow the simplified format when described in terms of average monthly performance. The amount of internal gain that is retained follows a non-linear curve. A straight line representing the overall UA heat loss coefficient gives the thermal balance of the building. Heating and cooling thermal loads are then the difference between the retained gain curve and the thermal balance line. With this algorithm, it is possible to compute thermal loads for heating and cooling on a monthly basis. As shown, the method accounts for solar gains. It also accounts for changes to thermostat setpoints or the amount of internal gains.

This method applies average weather variables as the forcing parameters. The primary variable is average outdoor dry-bulb temperature. Secondary weather variables (solar irradiation and relative humidity) are necessary for the simulation. These correlate closely on an average monthly basis and can be generated from the primary variable. Thus, the thermal computation operates using simple weather information that is readily available. Modeling is based on the actual local conditions rather than long-term average or “typical” (TMY) weather that may be a poor match to actual site conditions.

This second computation – that of computing plant energy -- is just basic physics. With some understanding of the conversion and delivery efficiency of the equipment, one can compute the amount of purchased energy consumed to satisfy the thermal loads. For example, if one knows the thermal loads and the hot/cold deck temperature difference, one can compute the volume of air needed to transfer the thermal energy. Then if one assumes the fan/duct efficiency, one can compute the electricity consumed to move that volume of air.

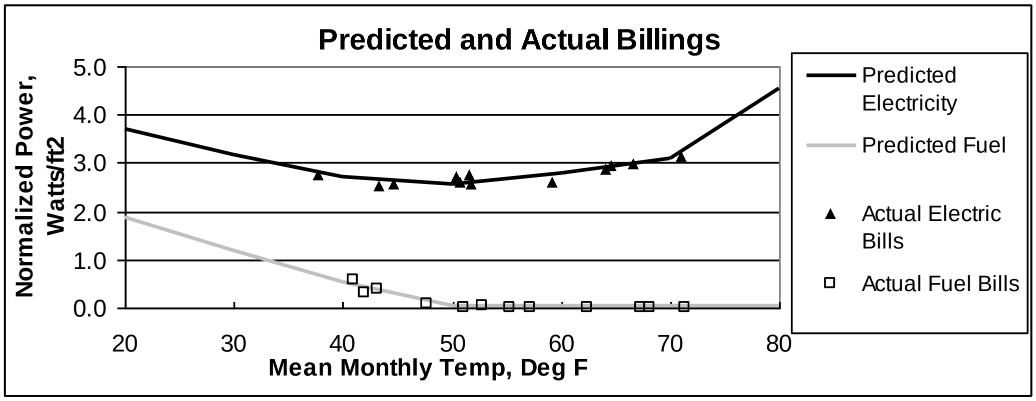

Figure 2. Operations Profile Example

Figure 2 shows average monthly energy use, normalized for building size, plotted against average monthly temperature. The advantage of this type of chart is that performance follows a similar profile over a range of climates -- hence; one building's performance can be compared to other facilities or under different climatic conditions.

"Tuning" or calibrating the model is the process of adjusting those enduses until the modeled performance matches the billing data. Even if billing data are not provided for a full year, a few data points are sufficient to distinguish if the facility has moved to a new operations profile.

The building in Figure 2 is an example of a run-around heat pump loop. One observes that the electricity performance profile is a U-shaped curve. The left side informs about the heating requirement; the right side informs the cooling requirement. The bottom of the U informs about the non-seasonal loads for lights and plugs. Hence, the shape of the U-curve informs us about the enduses within the facility.

The heat pump loop scavenges excess heat from other parts of the building; hence, heating fuel is needed only when average temperature falls below 8 deg C (47 degF). In that sense, this is an efficient building. However, the electricity usage is quite high. An energy audit showed older lighting fixtures with a high lighting power density and fair amount of office equipment. Even so, those enduses were insufficient to explain the high consumption. The conclusion was poor heating and cooling efficiency of the heat pump units. When these units were tested, that hypothesis was confirmed. The heat pumps were 25 years old and, although their performance was within original specifications, modern units would have a much better COP.

HVAC OPTIONS

For ease of use, the tool allows the user to select the type of equipment for several short pull-down lists. Based on the equipment selection, the tool then applies representative part-load performance curves in order to compute the equipment efficiency on a monthly basis. These curves have been derived from detailed review of many DOE2 simulations.

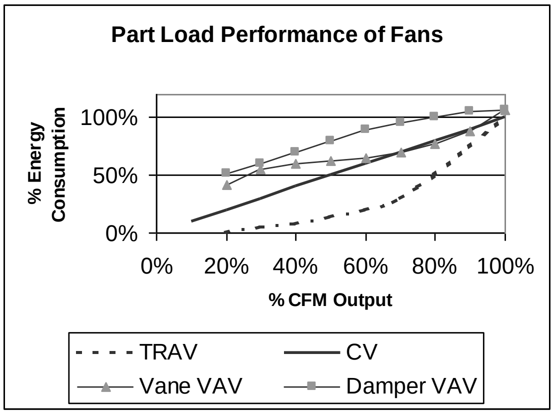

Figure 3. Example of Part Load Function

An example of one such part-load curve is shown in Figure 3, comparing the performance of different HVAC control options on fan operation. The Constant Volume (CV) fan is simply turned off/on in step increments to match need for airflow. Thus, its part-load response is completely linear. However, turning the fan off may not be allowable if ventilation rates are to be maintained. An attempt to modulate the airflow by restricting dampers leads to the most inefficient curve, greatly exceeding the CV line. Modulating the fan vanes is more effective but becomes inefficient at low flow rate. TRAV represents a digital control system that allows a Variable Speed Drive (VSD) with fan speed set based on the measured flow at the terminals. This is the most efficient type of control and closely approaches the ideal cube law for fan power.

Similar performance curves have been derived for cooling and heating equipment choices, including options for a run-around heat pump loop and commercial refrigeration.

VERIFICATION OF THE TOOL

Given that the calibration match occurs at the whole-building level, one can wonder how accurate the simplified tool is at identifying specific end-uses. Remember that the calibration process requires that the model match at all parts of the U-shaped operations curve. It turns out that to accomplish such a match, the end-uses have to be specified fairly well.

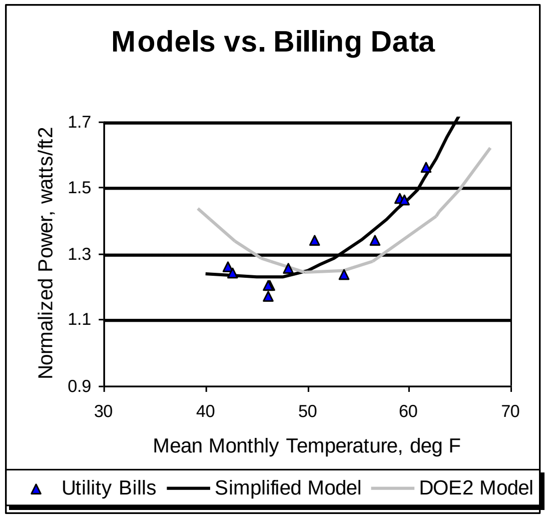

Figure 4. Comparison of Calibrated Models

An example of the difficulty in modeling for one specific site is shown in Figure 4. Actual billing data are shown as black triangles. The simplified model (black line) is in good agreement with the actual billing data (R^2= 91%). Notice that the DOE-2 model (gray line) departs from the actual billing data. The DOE-2 model shows more heating and less cooling for this particular building. The deviation reflects a fundamental problem with hourly models in general - that it is difficult to match actual consumption under actual weather with consumption using average (TMY) weather. Since DOE-2 requires complicated weather files, it is usually not possible to provide files based on actual weather, as it is possible with the simplified tool. Instead, the modeler runs DOE-2 using average or TMY weather and tries to compare some TMY points with some actual points. As this example shows, the DOE-2 matching step can be inaccurate.

The standard method of verifying a simulation tools compares results with a standard simulation (ANSI/ASHRAE Standard 140-2001: Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs). In the case of calibrated models, the simulations would all be expected to match the billing data. Hence, differences between modeling tools would not be readily apparent. Instead, we conducted a benchmark comparison between alternative modeling tools run under the same input parameters and with results expressed in terms of the expected energy savings. This method allows some check that end-uses are comparable between the two modeling tools. Results for calibrated savings estimates on 17 different sites are shown in Figure 5. The amount of savings predicted by the two methods varies greatly depending on the size of the facility. To simplify comparisons, results are presented as the Realization Rate or the ratio of the final, modeled savings to the initial design estimate. Perfect agreement between the two methods would result in observation aligned along a 45-degree line. As is apparent, the two modeling tools agree well.

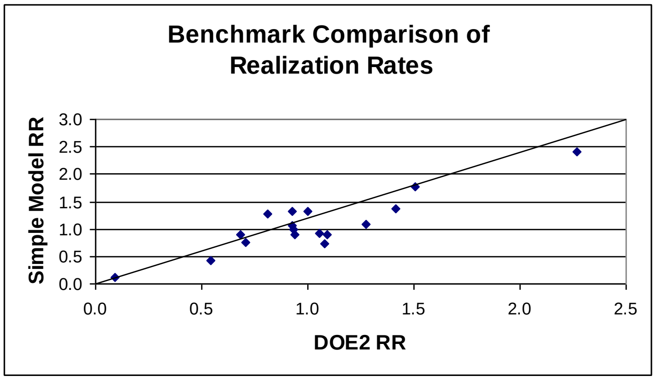

Figure 5. Comparison of Realization Rates

PRECISION OF THE ESTIMATE

Measurement and Verification (M&V) is an important part of any installation project. This task provides proof that installed measures are really working and may be necessary for performance-based contracts or shared savings arrangements to reassures fiscal managers that the investment was well spent. Verification is distinguished from commissioning as follows:

- Commissioning uses short-term tests or inspections during installation.
- Commissioning assures that measures are installed and operating as designed.
- Commissioning can't tell if the savings are there on a year-round basis or if design assumptions are off.

To the extent that a calibrated simulation model can verify that the expected savings are occurring, it constitutes a simple and low-cost form of commissioning. For small projects, where modest savings will not cover expensive on-site testing, this may be the most cost-effective commissioning option.

Verification over the long-term is an expectation for performance-based contracting. Typically, such contracting requires that all parties agree on:

- Baseline for estimating savings
- How to estimate partial savings during installation
- Interactive effects between measures
- Adjustments for weather, occupancy changes, or other changes that interfere with simply comparing the pre- and post-retrofit utility bills

Specifics of baseline conditions and adjustments away from baseline can be easily accomplished within the engineering model in a form that can be referenced as part of the agreement.

The standard reference for many Federal and international agencies is the USDOE sponsored International Performance Measurement and Verification Protocol (IPMVP). This protocol may seem intimidating but is a series of commons-sense guidelines. The IPMVP protocol presents several Measurement and Verification (M&V) options; in this case, we focus on Option D, specified as the use of calibrated engineering simulation models.

There is one important new requirement – the IPMVP asks for precision estimates (error bands) on savings. For example, if one computes savings of 100,000 kWh, one should also be able to state that the 90% Confidence Limit of this estimate is +/- 20,000 kWh. Such a precision estimate is not a result that engineers typically provide. This brings up the question -- how accurate are modeled estimates?

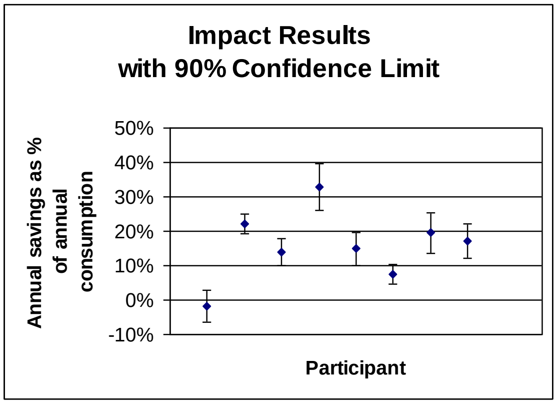

Figure 6. Precison of Results

We have participated in several studies to verify savings following IPMVP guidelines, including one report for a World Bank-funded overseas project. In general, there is a certain amount of "noise" matching actual consumption data to modeled simulations. Causes include undocumented changes in building operation as well as uncertainty in the modeling methodology. Pre-retrofit conditions were rather noisy. Typical Standard Errors of the annual consumption estimate would be about 2% for both the pre- and post-retrofit year. The Standard Error of the savings is based on the difference of these two annual estimates in quadrature or about 2.8% of the annual pre-retrofit whole-building consumption. For annual savings are estimated at 15%, 90% confidence limits would be about 4.6% of total consumption. That is, one is able to distinguish savings of 15% plus or minus 5%. Thus, the precision of this method is clearly quite sufficient to provide a reliable savings estimate and is as good, if not better, than could be expected for any whole-building modeling tool.

Some examples of precision for typical savings estimates are shown in Figure 6. For the first participant, savings were slightly negative and not statistically significant. Investigation determined that the conservation measures were not appropriately installed in this case. For the other participants, the savings estimates were strongly positive and significantly different from zero. In this study, confidence limits of about +5% of annual consumption are about 30% of the savings estimate. This level of accuracy is quite sufficient to eliminate the null hypothesis and provide creditability to the estimates.

APPLICATIONS

Adjust Baseline for Changed Conditions

Figure 7 shows an example of a modeling problem. In this case, a school installed efficient lighting. Yet shows that the predicted and actual bills (gray and white bars) are not in agreement. The bills did not decrease as expected. What happened?

The school staff explained the change. Due to a community concern to keep kids off the street, the school instituted a midnight basketball program. Now the gym is open 24 hours.

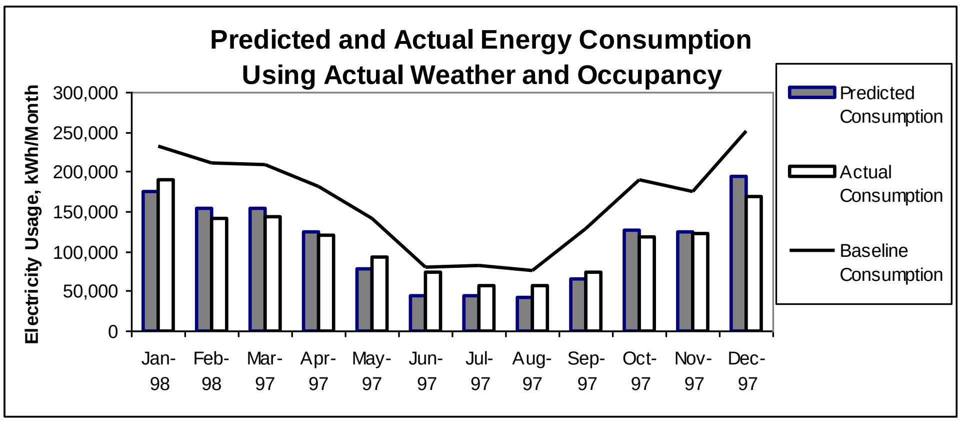

Figure 7. School Retrofit

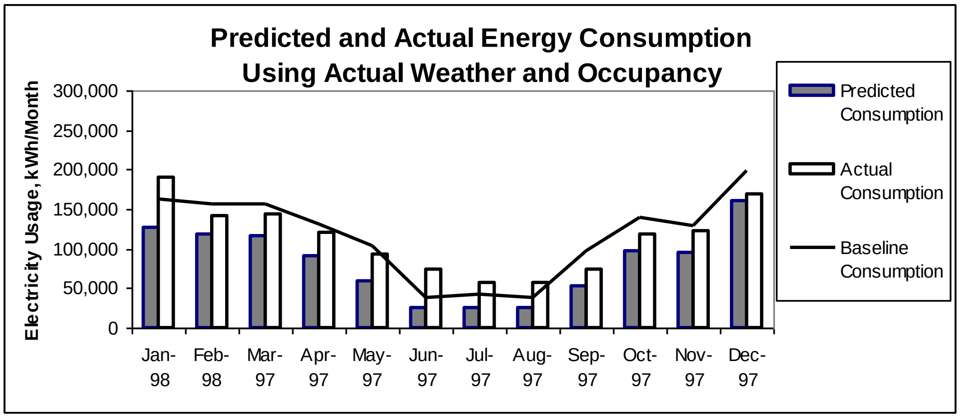

Figure 8. Revised School

When the model is revised to include the new operating hours, we see a better picture of the operation in Figure 8. Now it is clear that the consumption is close to that expected and there are large savings compared to what the old facility would have used with longer operating hours. This is an example of using the model to create a "hypothetical" baseline. Often the retrofit opportunity is used to remodel or change other operations. The old baseline is no longer relevant to the changed facility. Yet, because the model is based on engineering parameters, it is not difficult to adjust for the changed conditions.

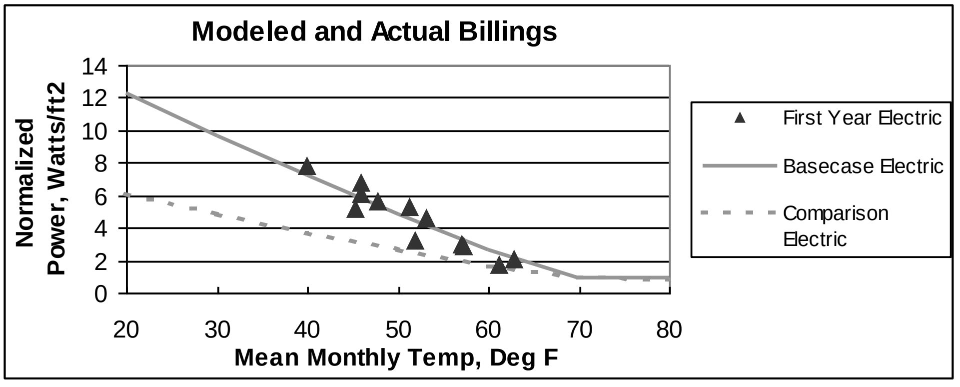

Figure 9. College Modeled With OSA

Review Operations

The process of matching bills often reveals information that was not apparent. For example, Figure 9 shows electricity use for a community college campus. An energy audit was conducted and the resulting site description (insulation values, lighting density, etc) has been included in the model. The dashed line shows what the initial model would have expected for the operations profile. Yet actual energy use is much higher than expected. How do we explain this difference?

Answer: Excess Outside Air! To get a model that matches the bills, one must assume a high ventilation rate as shown in the solid line in Figure 9. This is equivalent to the facility being ventilated at full design rate for 24 hours per day, seven days a week. Is this even possible? When the facility manger was queried, he acknowledged this fact; the building's fans were running full-time without any controls. Simple time clock controls could provide savings of about 1 million kWh per year.

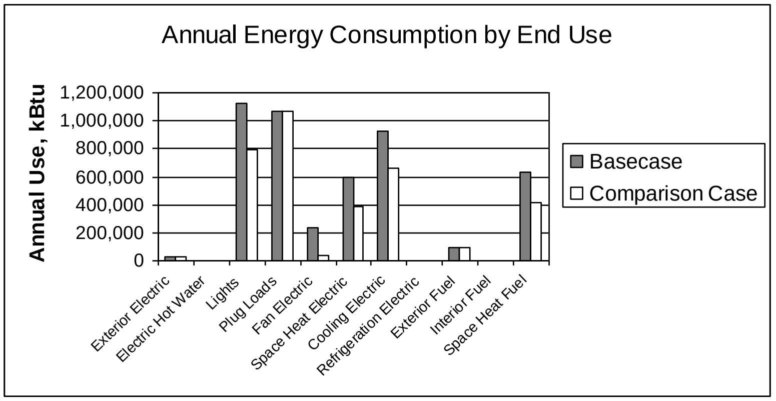

Figure 10. Annual Enduse Breakdown

Review Enduse Breakdown

The enduse breakdown falls out of the operations profile above. These components are tabulated on an annual basis and provide a useful check as shown Figure 10. For example, suppose a vendor estimates savings for efficient fans. How does that estimate compare to the modeled estimate of total fan energy? Are the savings realistic? The simulation tool provides a way for a manager to quickly check on specific enduses.

Set Performance Targets

Verification is a unique application for this tool. One can forecast what future consumption is supposed to be. Then, as the future bills come in, they can be checked against the predictions. This answers the question: "Is this building on track for savings?" In this sense, it provides a simplified commissioning check. For facilities without a large budget, this may be the only affordable type of commissioning.

CONCLUSIONS

- A simplified modeling tool linking utility bills and engineering simulation provides similar results to complicated engineering models, but with greatly reduced data requirements.
- The tool quickly matches to actual bills and weather, providing a tuned, as-built model.
- The tuning process offers a breakdown of energy enduses, may reveal major operations problems, provides realistic calibrated savings estimates and is a mechanism for on-going quality assurance.
- The tuned model generates performance targets that are a simple-level form of commissioning or performance verification at low cost.
- The method simplifies reporting the precision of the savings estimate, as expected for the IPMVP verification protocol.

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