BUILDING ENERGY SIMULATIONS FOR DESIGN, EVALUATION, COMMISSIONING, CONTROL AND DIAGNOSTICS

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ABSTRACT

The most common use of building energy simulations, by far, is in the design of buildings, especially non-residential ones. It is a common perception that the simulations ought to be useful for many other applications, such as commissioning, control and diagnostics. A distinguishing feature of the latter applications is that they require linking with monitored data, and this link must be addressed before the applications can be realized. In linking with data, the following dilemma arises: only a small number of parameters can be reasonably estimated from typical building performance data whereas a realistically complex model of the building has a large number of parameters. This dilemma is resolved and the mathematical sophistication of microdynamic simulations (i.e., simulations such as DOE-2 which simulate each component) is brought to bear on the problem by a technique called PSTAR (Primary and Secondary Terms Analysis and Renormalization). This allows a simulation of the as-built building, and provides the required link with performance data. The results for a test building are presented. The role of the different heat flow terms in determining the building performance are elucidated. Applications to commissioning, control and diagnostics are outlined. Further developments necessary for field applications are pointed out.

I. INTRODUCTION

The primary purpose of building energy simulations is generally viewed to be in the thermal evaluation of a building in the latter stages of its design. Preparation of detailed input files is, even with the increase in the user-friendliness of simulation codes, still time-consuming, especially for non-residential buildings. If this effort results in not only design evaluation but other applications, it should make the use of simulations more attractive. Several researchers have remarked that the simulations ought to be useful for other applications, such as building commissioning, control and diagnostics.

All of the above additional applications require linking with building performance data. Since one of the strengths of simulations is to deal with dynamic performance, we are primarily concerned with dynamic - typically hourly - data. Very useful information can be obtained from an analysis of time-integrated data, such as utility bills; it is not considered here. Also, we shall consider a feasibly small number of data channels - no wall temperatures, no measurements of material properties, etc. Similarly, for HVAC systems, we shall typically assume only flow and temperature measurements.

Linking simulations with performance data has been a serious problem in building energy analysis. While the capabilities of simulation codes to model ever more complex heat flows are increasing, their systematic use in applications other than in design problems is generally lacking. This, we believe, is due mainly to the following two reasons: (a) it is generally not feasible to measure all the inputs to simulations - material properties, etc; also, some features may be hidden. (b) despite their sophistication, approximations of uncertain impact are generally made in the algorithms - such as one dimensional heat flows through walls, distribution of solar radiation on various surfaces, etc.

Whenever performance data are to be analyzed, the common practice has been to resort to treating the building as a "black box" whose parameters are estimated through identifications techniques - ARMAX (AutoRegressive Moving Average with eXogenous inputs) model or equivalent circuits [Ref. 1]. This necessarily results in the following dilemma: In order to take into account the many driving functions and the complexities of building responses, it is necessary to have a large number of parameters. However, only a small number of parameters can be estimated within acceptable bounds from performance data. Since the latter is an overriding consideration, the tendency has been to work with oversimplified models.

A technique, called PSTAR (Primary and Secondary Terms Analysis and Renormalization) has been developed [Ref. 2] that resolves this dilemma. The user-friendliness and mathematical sophistication of building energy simulation codes is increasing. At the same time, data acquisition systems for monitoring the building and

equipment are becoming increasingly sophisticated. A well-defined technique is given to couple the two.
After a brief explanation of the PSTAR technique, results for a test building are given. Application to the commissioning, control and diagnostics problem is outlined. A summary is given in Sec. V.

II. PSTAR: A SUMMARY

In the design problem, the building is simulated with typical driving functions - ambient weather, solar radiation, wind speed, etc. An actual building can be simulated with measured driving functions. If the simulated performance, as is most often the case, does not agree with the measured performance, how does one reconcile the difference? An obvious attempt is to modify the inputs of the simulation in some manner. It is difficult to make a systematic modification of the large number of inputs. The PSTAR approach to reconcile the differences is as follows: disaggregate the various heat flows $Q_1, \ldots, Q_n$ contributing to energy balance of the zone or building. The discrepancy between the simulated and measured performance is reflected by the fact that the various energy flow terms will not add up to zero. A term such as electrical energy is directly measured and is well-determined. Classify the remaining terms as primary or secondary according to the following criterion. A term is primary if there are periods when it is large in magnitude; otherwise, it is secondary. Let $Q_1, \ldots, Q_k$ be the primary terms, $Q_{k+1}, \ldots, Q_m$ be secondary and $Q_{m+1}, \ldots, Q_n$ be directly measured flows. Introduce renormalization parameters p_i for the primary terms to be determined by a linear least squares to give energy balance over the monitoring period:

$$p_1 \cdot Q_1 + \ldots + p_k \cdot Q_k + Q_{k+1} + \ldots + Q_m + Q_{m+1} + \ldots + Q_n = \text{(best fit) } 0.$$

This renormalized energy balance equation is used in applications.

Note the following:

(1) Instead of treating the building as a "black-box", the PSTAR technique starts with a building and a HVAC model derived from a site visit and manufacturer's data. We shall refer to this model as the audit model. It is the departure of this model from "as-built" model that is obtained from performance data. The idea can be summarized as: "first take your best shot at modeling, and then renormalize to fit short-term data".

(2) The technique is applicable to multizone buildings.

(3) If the audit model accurately represents the as-built building, and if the simulation code is accurate, the renormalization parameters should all be one. Thus the deviation from unity is a measure of the accuracy of the audit model and of the simulation code.

(4) If in doubt about whether a term is primary or secondary, a renormalization parameter can be introduced for it. If it is a secondary term, its renormalization parameter is (and possibly others are) either unreasonably away from one and/or has large uncertainty of estimation. In that case, a recalculation treating this term as secondary can, if necessary, be performed.

(5) A graph of the various heat flow terms as a function of time is extremely useful: (a) to understand the relative magnitudes of the various heat flows at different times, (b) to decide whether a term is primary or secondary, and, (c) to study the correlation between various terms, which, of course, is essential to understand variances and covariances in the parameter estimates.

(6) The identification of the various disaggregated heat flows, as well as their calculation is quite intricate. Although we have discussed multiplicative renormalization parameters, situations may arise where other types of renormalization parameters are necessary.

(7) Using the least squares criterion, usually all the parameters are estimated simultaneously. We find that in building energy applications, there usually are large correlations among certain parameters, e.g., load coefficient and solar gains. This correlation can be made small by selecting shorter segments of data where a smaller number of parameters are estimated. This sequential and iterative estimation is essential.

(8) Once the renormalization parameters are identified, a test protocol naturally emerges. The test protocol is designed to elicit the parameters.

(9) Validation of the PSTAR Procedure is discussed in Refs. 3 and 4. Ref. 4 also gives additional details of the results from the test house.

III. THE TEST HOUSE

In this section, the general considerations of Sec. II are demonstrated with data from a test building. The test building is an unoccupied and unfurnished 1007-ft^2, single-story building with a crawl space, and well-insulated lightweight frame walls. A layer of brick pavers placed on the floor on the south side provides heat storage. The glazing orientations are 99.1 ft^2 on the south, 32.6 ft^2 on the east, 54.3 ft^2 on the west, and 55.1 ft^2 on the north. The equivalent leakage area measured by a blower door test was 40 sq. in.

The Energy Balance Equation

For the test house, the energy balance equation, at hour i, can be written as (Sign convention: a positive value of any term is a heat gain by the air node, negative value a heat loss.):

$$p_0.[-L.\{T_{in}(i) - T_{out}(i)\}] + p_{in}.Q_{in,storage}(i) + p_{sun}.Q_{sun}(i) + p'_{sun}.Q_{sun,shift}(i) + p_{aux}.Q_{aux}(i)$$

$$+ \Delta Q_{infiltration}(i) + [-L_{bsm}\{T_{in}(i) - T_{bsm}(i)\}] + Q_{out,storage}(i) + Q_{sky}(i) + Q_{rest}(i) +$$

$$Q_{electric}(i) = 0.$$

The first group contains the primary terms, the second the secondary terms, and the third the measured term. We shall briefly explain the terms below.

$-L.\{T_{in} - T_{out}\}$: the static loss due to inside-outside temperature difference. L is the building load coefficient; this includes a component due to infiltration under T_{in}-T_{out} of 43.6°F, and a wind speed of 7.3 mph. (These were the conditions during the coheating part of the test - i.e., when a steady temperature was maintained during the night with electric heat.)

$Q_{in,storage}$: The discharge/charge of masses due to inside temperature variations. This term is small if T_{in} is maintained constant, but during periods of rapidly changing T_{in} (e.g., during cool down and heat up) it is large and is a primary term.

Q_{sun} : Solar gains. This term is usually small at night time, but is a primary term during daytime, especially on a sunny day. It is necessary to consider solar gains by the air node from multiple orientations and angles of incidence in the presence of shading devices, etc. $Q_{sun,shift}$ accounts for discrepancies between the <u>phases</u> of audit and actual solar gains; a pure multiplicative renormalization of Q_{sun} alone cannot accomplish this. As it turned out for the test house, $Q_{sun,storage}$ is a small term, and could have been ignored.

Q_{aux} : The auxiliary heating/cooling supplied by the space-conditioning system. This is zero during free-floating conditions, but is a primary term during cold/warm periods.

$\Delta Q_{infiltration}$: the load coefficient includes a component due to infiltration. Infiltration is, however, variable. This term accounts for the variation in infiltration heat flow around the base value.

$-L_{bsm}[T_{in} - T_{bsm}]$: the static loss due to the difference between the inside temperature T_{in} and the basement temperature T_{bsm}; L_{bsm} is the conductance between the inside and the basement. (Basement is used here to denote the crawlspace.) For a slab-on-grade floor, this term would be replaced by the heat flow due to the floor.

$Q_{out,storage}$: When T_{out} is changing, the mass coupled to T_{out} (such as mass in the exterior walls outside the insulation) do not respond instantaneously. This results in a correction term.

Q_{sky} : The sky temperature is depressed below ambient resulting in additional heat loss. This depression depends on a number of factors, primarily cloud cover and humidity.

Q_{rest} : this term catches all effects not included above.

$Q_{electric}$: the electric heat input

Calculation of the Heat Flow Terms: This is discussed in detail in Ref. 2. We shall simply note here that (a) some terms such as $-L.\{T_{in} - T_{out}\}$ are very easy to calculate, (b) certain terms such as $Q_{in,storage}$ are computed macrodynamically - i.e., by computing the whole building or zone response, and (c) the terms Q_{sun} and Q_{rest} are computed microdynamically, i.e., using a microdynamic simulation, such as DOE-2 or SUNCODE; the simulator chosen should have the ability to model all features of interest. Some of these features may be: spatial non-uniformity of T_{in}, wind-dependent convection on exterior surfaces, radiative heat transfer from the bottom of the floor to the basement/crawl-space floor and walls, variation in material properties with temperature, etc. We shall not pursue this any further, since we have not simulated our test building on a code that takes into account the features listed above.

IV. RESULTS

Short-term tests were done on the test building during January 31 - February 2, 1988. The quantities measured were: T_{in}, T_{out}, T_{bsm}, $Q_{electric}$, wind speed, solar radiation on a vertical surface and global horizontal, and relative humidity. From these, the various heat flows are obtained. SUNCODE [Ref. 5] was used as the microdynamical simulation for the solar gain calculations. The parameters obtained from a least squares fit are listed in Table I. (Instead of p_0, the load coefficient is directly listed).

The various heat flows and the residual after the best fit are shown in Figs 1 and 2. The error term is also shown in Fig. 1. The renormalized energy balance equation gave an energy balance during the test period with a standard deviation of 689 Btu. The error is likely reduced by evaluation the Q_{rest} term.

We will next outline various applications.

TABLE 1

	Renormalized	Audit
p_{in}	1.20	1
p_{sun}	0.843	1
p'_{sun}	-0.023	0
Q(rms)(a) Btu/h	689	
Load Coefficient(b) (Btu/h.°F)	197	270

(a) Denotes the root-mean-square energy imbalance over the fit period after the least squares fit.

(b) Includes a component due to infiltration under T_{in}-T_{out} of 43.6°F and a wind speed of 7.3 mph.

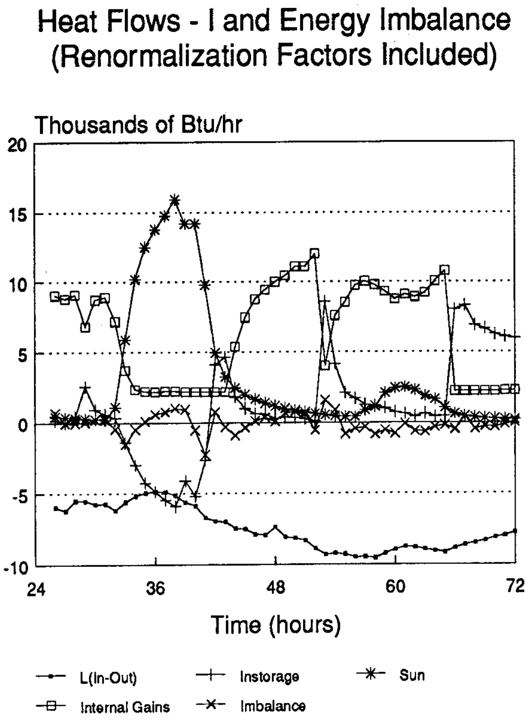

Figure 1: Plot of the primary heat flows -197[T_{in}-T_{out}], 1.20*$Q_{in,storage}$, 0.843*Q_{sun},$Q_{electric}$, and the energy imbalance.

a. Evaluation and Commissioning

As part of commissioning, one would like to compare the actual performance of the building and the HVAC systems with the design performance; it is this part that we wish to address. The important issues relating to air balancing and controls operation are not addressed.

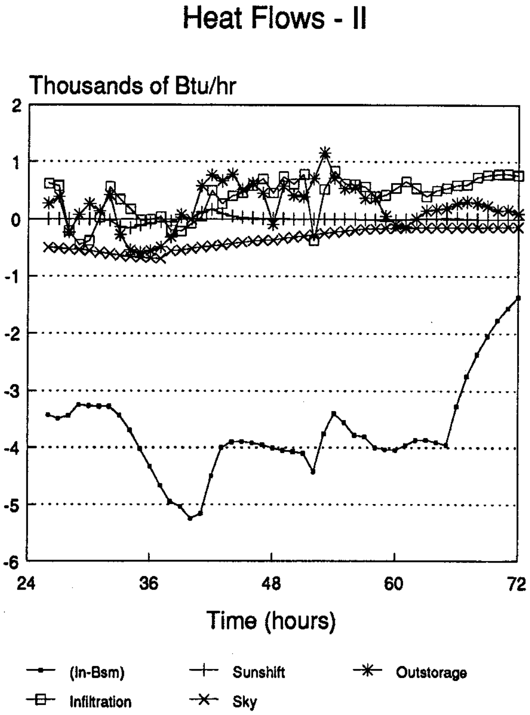

Figure 2: Plot of the heat flows -0.023*$Q_{sun,shift}$, -L_{bsm}*[T_{in}-T_{bsm}], $Q_{out,storage}$, $\Delta Q_{infiltration}$, and Q_{sky}.

We wish to compare the design (i.e., audit) parameters with the measured ones, with a view to assessing the conformity of the actual building to the design building; the differences should be attributable to materials and/or workmanship. In order to do this meaningfully, it is necessary to establish the accuracy of the audit as well as the measured parameters. As we see below, even a relatively simple quantity to calculate, namely the load coefficient, poses a considerable problem in this error analysis. As far as the PSTAR analysis is concerned, the validation studies referred to earlier are being continued for this purpose.

Let us now compare the measured value of the load coefficient with the audit value. The skin conductance from an audit description was 204.8 Btu/h.°F, and the blower door model value for infiltration was, as mentioned before, 62.1 Btu/h.°F, for a total of 266.9 Btu/h.°F. This is considerably higher than the "measured" value of equal to 196.8 Btu/h.°F. (This is contrary to the expectation that measured load coefficient is larger than or equal to the audit value depending on workmanship. In fact, this trend has been observed in almost all of the residential buildings we have monitored so far.) Can we attribute the difference to materials and/or workmanship? As stated before, we need to study the errors in the two numbers; these will be reported elsewhere. There can be cases where the measured load coefficient is clearly different from the audit value; in the case of one non-residential building, the measured load coefficient turned out to be twice the audit value. [Ref. 6].

The parameter p_{sun} was 0.843. (The average over thirteen repeated tests performed over a four month period was 0.83 ± 0.05.) This implies that the actual solar gains are 84.3% of the audit solar gains. A number of factors - unaccounted shading, dust, use of a combined convection-radiation coefficient - contribute to this difference. The parameter p'_{sun} was -0.023; this implies no significant phase correction for solar gains was needed.

The parameter p_{in} was 1.20. (The average of the thirteen tests was 1.12 ± 0.09). This implies that the effective heat capacitance is somewhat higher than the audit value.

Another useful comparison, not discussed here, is the annual loads from a simulation of the audit building and from the renormalized building. On a different building with a heat pump, we have compared the heat output based on manufacturer's specifications with the heat delivered based on calorimetry. The difference gives an estimate of the duct losses as well as any departure of the actual output compared to manufacturer's specifications.

b. Control

Let us first consider, predictive control. With the renormalized energy balance equation, it is quite straightforward, given the expected weather, to predict load profiles and thereby determine optimal morning start-up, the effect of precooling, as well as ice storage. These issues are usually addressed using empirical models [Ref. 7]. With improved thermal modeling and weather prediction, the control operation can be better tuned. Whether improvements in thermal modeling are worthwhile or not is ultimately determined by imperfections in weather prediction.

For real time control, it is essential to couple the renormalized building model with renormalized HVAC models, and use shorter time steps. This requires, of course, a significant development effort.

c. Diagnostics

The renormalized energy balance equation allows a simulation of the as-built building. The various terms contributing to energy balance are expected to add up to zero within certain tolerance. If they do not, one or more of the terms is significantly different from the expected value. This provides a certain level of global diagnostics. It does not pinpoint which of the terms should be tackled, much less which component - building or HVAC - needs attention. Since the data required for such global diagnostics is largely available from the energy management system, the incremental cost for this global diagnostics is minimal.

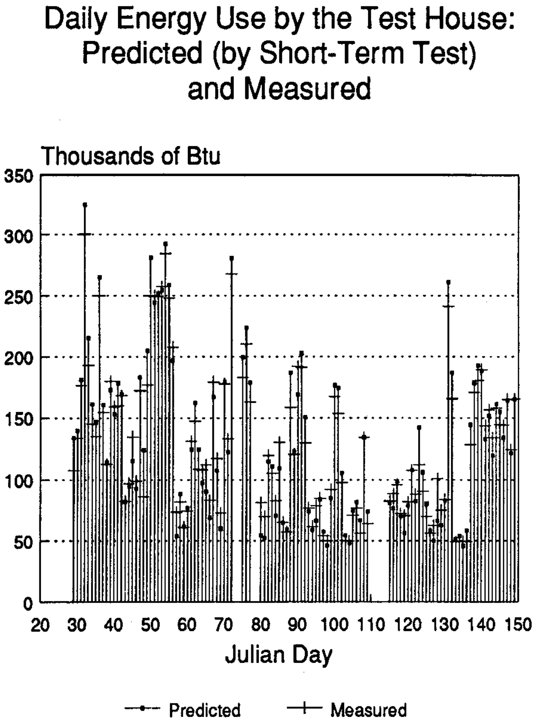

Figure 3: Measured daily energy use is compared with that predicted by the renormalized building model obtained from the short-term tests done on Julian days 31-32. (Gaps correspond to days with missing data.)

In order to illustrate the general procedure, we shall use the renormalized energy balance equation obtained from the tests discussed above to determine the expected performance of the building during the entire monitoring period Jan 30 - May 1, 1988. Fig. 3 and 4 show the predicted daily total heating energy and the measured values. (Hourly comparisons are also possible.) The good agreement during the controlled conditions indicates that during normal operation, a disagreement can be attributed to problems with one or more of the terms in the energy balance.

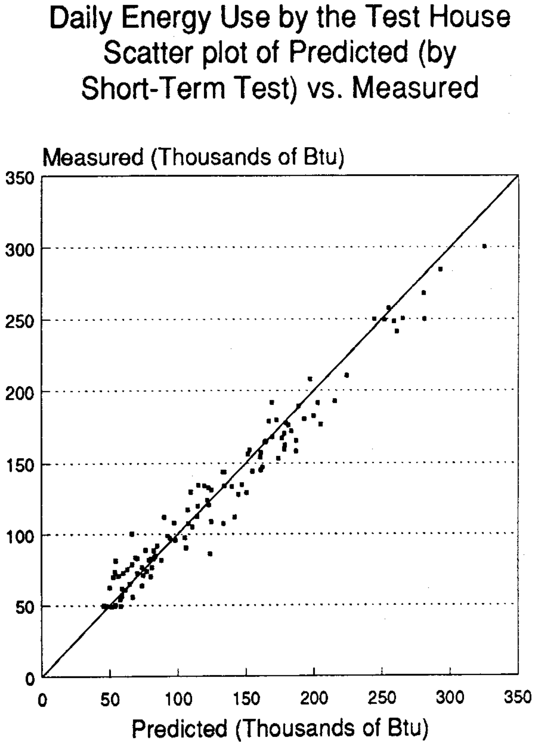

Figure 4: The same data as in Figure 3, but shown as a scatter plot. Best fit gives (measured) = (0.967±0.008) times (predicted)

V. SUMMARY

The most serious obstacle to the use of sophisticated simulations in commissioning, control and diagnostics has been the lack of a method to simulate the as-built building (which typically shows significant deviations from overcome by the PSTAR technique by synergistically combining microdynamic simulations, macrodynamic computations, and performance data to arrive at an energy balance for the as-built building.

We have given an explicit mathematical formulation for using existing or future microdynamical simulations in the commissioning, control and diagnostics problems. A study of several buildings we have monitored to-date appears to show certain biases in simulations. This points to needed improvements in the simulators. A study of the terms in the energy balance shows their relative importance and the requirements on the accuracy of the models and measurements that go into their determination.

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