SERI/TP-253-2661
UC Category: 59b
DE85008815

Building Parameters and Their Estimation from Performance Monitoring

K. Subbarao

May 1985

Prepared for
ASHRAE Annual Meeting
Honolulu, Hawaii
22-25 June 1985

Prepared under Task No. 3753.31
FTP No. 527

Solar Energy Research Institute
A Division of Midwest Research Institute

1617 Cole Boulevard
Golden, Colorado 80401

Prepared for the
U.S. Department of Energy
Contract No. DE-AC02-83CH10093

NOTICE

Printed in the United States of America
Available from:
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

Price: Microfiche A01
Printed Copy A02

TP-2661

Building Parameters and Their Estimation from Performance Monitoring

K. Subbarao*

ABSTRACT

This paper defines parameters that characterize the statics and dynamics of a building. A static parameter is the familiar building loss coefficient that we can calculate using element-by-element addition or determine from building performance data by regression. The dynamic parameters are obtained from a natural generalization of the static parameters. These parameters thus share the same characteristics. In this paper we define eight parameters for a one-zone building and give the results from actual performance data, pointing out extensions and applications. This method is referred to as BEVA (Building Element Vector Analysis).

INTRODUCTION

The variable base degree day (VBDD) method (Kusuda 1982) for analyzing energy in a conventional building not only calculates auxiliary heating energy, given the building description (the forward process), but also determines the building loss coefficient, given the auxiliary heating energy (the inverse process) (Fels 1984). This method is popular because it is applicable to both the forward and the inverse processes and deals with quantities that are accessible to simple, whole building measurements. When we consider buildings outside the range of validity of the degree day method, we find a situation that has not been equally satisfactory. Buildings where dynamical effects are important fall in this category.

Although passive solar buildings have unambiguously demonstrated energy savings (SERI 1983), analyzing their performance data using the same methods by which they were designed has been rather inconclusive. This is because the method generally used for the forward process (namely detailed simulations or their derivatives) deals with quantities that are not accessible to simple whole-building (or zone, in the case of multizone buildings) measurements.

This paper describes a method of analysis that is a natural dynamical extension of the VBDD called BEVA (Subbarao 1984; Subbarao et al. forthcoming). It has been successfully demonstrated in a few cases, and additional applications are being actively pursued.

BUILDING PARAMETERS AND THEIR PHYSICAL SIGNIFICANCE

The VBDD method involves two building parameters: the loss coefficient, L, and the equivalent clear aperture area, S_o, for solar gains. These characterize building statics. To include dynamics we introduce additional parameters. We will outline what these are, what significance is, how they are calculated from a building description (the forward process), and how they are determined from monitored data (the inverse process).

---

*K. Subbarao is a physicist in the Thermal Research and Engineering Branch, Solar Energy Research Institute, Golden, CO.

Three pairs of numbers are the minimum parameters needed to characterize building dynamics. Just as the building loss coefficient gives us the total conductance from all paths, these dynamical parameters give the combined effect of all thermal masses along with their couplings to indoor air and to solar radiation. Since there are three primary drivers of heat flows--the indoor temperature, T_{in}, the outdoor temperature, T_{out}, and solar flux, Q_{sun}, on the south orientation--we introduce three pairs of numbers. (Internal gains, Q_{int}, and auxiliary energy, Q_{aux}, are considered instantaneous heat gains by room air and therefore do not require additional dynamic parameters; if not instantaneous, they too require additional parameters.)

The three pairs of numbers can be represented by three, two-dimensional vectors, $\vec{V}$, $\vec{W}$, and $\vec{S}$. We will now discuss the physical significance of these vectors. Suppose

$$T_{out} = \text{constant} = \bar{T}_{out} \tag{1}$$

$$Q_{sun} = 0 \tag{2}$$

$$Q_{aux}(t) = \bar{Q}_{aux} + \Delta_{aux} \cos 2\pi t/T \ , \tag{3}$$

where T is the period of the swing; T = 24 hours gives the diurnal variation. Then the indoor temperature, T_{in}, is given by

$$T_{in}(t) = (\bar{T}_{out} + \bar{Q}_{aux}/L) + \Delta_{in} \cos 2\pi/T(t - t_{lag}^{in}) \ . \tag{4}$$

The inside temperature swing $2\Delta_{in}$ is proportional to the swing $2\Delta_{aux}$ in the auxiliary. Let us define the quantity Δ_{aux}/Δ_{in} as V. The indoor temperature lags behind the auxiliary by t_{lag}^{in} hours. Let us convert the lag into an angle: $\phi_v = 2\pi/T \, t_{lag}^{in}$. The pair of quantities (V,ϕ_v) can be represented by a vector $\vec{V}$ with length V oriented at an angle ϕ_v with respect to a reference axis. The vector $\vec{V}$ depends on the period T; we will choose T = 24 hours to characterize the building.

Under the following conditions, we see that

$$T_{in} = \text{constant} = \bar{T}_{in} \tag{5}$$

$$Q_{sun} = 0 \tag{6}$$

$$T_{out}(t) = \bar{T}_{out} + \Delta_{out} \cos 2\pi t/T \ . \tag{7}$$

The auxiliary needed to maintain a constant indoor temperature is given by

$$Q_{aux}(t) = L(\bar{T}_{in} - \bar{T}_{out}) + \Delta_{aux} \cos 2\pi/T(t - t_{lag}^{out}) \ . \tag{8}$$

As before, the ratio $\Delta_{aux}/\Delta_{out} = W$ and the angle $2\pi/T \, t_{lag}^{out} = \phi_w$ can be represented by a vector $\vec{W}$.

Under the following conditions, we see that

$$T_{in} = \text{constant} = \bar{T}_{in} \tag{9}$$

$$T_{out} = \text{constant} = \bar{T}_{out} \tag{10}$$

$$Q_{sun} = \bar{Q}_{sun} + \Delta_{sun} \cos 2\pi t/T \ . \tag{11}$$

The auxiliary heat needed to maintain a constant indoor temperature is given by

$$Q_{aux}(t) = [L(\bar{T}_{in} - \bar{T}_{out}) - S_o\bar{Q}_{sun}] - \Delta_{aux} \cos 2\pi/T(t - t_{lag}^{sun}) \ . \tag{12}$$

As before, the ratio $\Delta_{aux}/\Delta_{sun} = S$ and the angle $2\pi/Tt_{lag}^{sun} = \phi_s$ can be represented by a vector $\vec{S}$.

The three pairs of quantities, $\vec{V}$, $\vec{W}$, and $\vec{S}$, characterize building dynamics. Together with the static parameters L and S_o they give a total of eight parameters for a simple one-zone building. The building loss coefficient, L, is an element-by-element sum of conductances of individual elements. So is the clear aperture area, S_o. Similarly the vectors are element-by-element sums of individual vectors. The vector addition is shown in Figure 1 for the $\vec{W}$ vector. Thus, we can calculate all the building parameters, L, S_o, $\vec{V}$, $\vec{W}$, and $\vec{S}$, from a building description.

DETERMINING THE BUILDING PARAMETERS FROM PERFORMANCE DATA

The building parameters can be determined from suitable performance data. Monthly data are usually adequate to determine the static quantities. To determine the dynamical parameters we need finer data. Suppose we have averages over intervals of Δ (Δ is usually an hour) of T_{in}, T_{out}, Q_{sun}, Q_{aux}, and Q_{int}. . Let $T_{in}(n)$ denote the average between $(n-1)\Delta$ and $n\Delta$ and do the same for the other quantities.

The theory behind the steps involved in determining the building parameters is given in Subbarao (1984) and Subbarao (forthcoming). The heat balance equation can be rewritten as

$$\sum_{k=0}^{N_{in}} a_k^{in} T_{in}(n-k) - \sum_{k=0}^{N_{out}} a_k^{out} T_{out}(n-k)$$

$$- \sum_{k=0}^{N_{sun}} a_k^{sun} Q_{sun}(n-k) = \sum_{k=0}^{N_{aux}} a_k^{aux} Q_{aux}(n-k) \qquad (13)$$

(For simplicity we include here the internal gains in the auxiliary term.) The integers N_{in}, N_{out}, N_{sun}, and N_{aux} are chosen conveniently, usually to be between one and three. We can show that

$$L = \sum a_k^{in} / \sum a_k^{aux} \qquad (14)$$

$$S_o = \sum a_k^{sun} / \sum a_k^{aux} \qquad (15)$$

$$V = r_{in}/r_{aux} \qquad (16)$$

$$\phi_v = \phi_{aux} - \phi_{in} \qquad (17)$$

$$W = r_{out}/r_{aux} \qquad (18)$$

$$\phi_w = \phi_{out} - \phi_{aux} \qquad (19)$$

$$S = r_{sun}/r_{aux} \qquad (20)$$

$$\phi_s = \phi_{sun} - \phi_{aux} \quad . \qquad (21)$$

Equations 14 through 21 give the eight building parameters in terms of the regression coefficients "a." The quantities r_{in} and ϕ_{in} are given by

$$r_{in} \cos \phi_{in} = \sum a_k^{in} \cos 2\pi k/T \qquad (22)$$

$$r_{in} \sin \phi_{in} = \sum a_k^{in} \sin 2\pi k/T \ . \qquad (23)$$

We can obtain the quantities r_{out}, ϕ_{out}, r_{sun}, ϕ_{sun}, r_{aux}, and ϕ_{aux} by relations similar to Equations 22 and 23 with changes.

Given the performance data, all of the a-coefficients can be obtained from a linear regression. This can be done as follows: in Equation 13 move everything except the a_0^{in} $T_{in}(n)$ term to the righthand side. Choose $a_0^{in} = 1$. This equation predicts $T_{in}(n)$ from measured past values of T_{in} and measured past and present values of T_{out}, Q_{sun}, and Q_{aux}. Choose the regression coefficients to minimize the sum (over n) of the squares of the deviations between measured and predicted values of $T_{in}(n)$. (We can alternatively choose the regression coefficients to give the best predictions of auxiliary energy.) There is actually a linear constraint $\Sigma a_k^{in} = \Sigma a_k^{out}$. So a total of $N_{in} + N_{out} + N_{sun} + N_{aux} + 2$ coefficients are obtained by regression and then transformed into the building parameters.

We applied this analysis to a test cell at SERI (Subbarao 1984; Subbarao et al., forthcoming). Because of certain constraints on the operation of the test cell, the data can only give L, S_o, W/V, $\phi_w - \phi_v$, S/V, and $\phi_s - \phi_v$. The results of the analysis are given in Table 1. Two different runs were made with the same data. The only difference between the two runs was in the values of N_{in}, N_{out}, N_{sun}, and N_{aux}. Although the a-regression coefficients differ in the two runs with no apparent pattern, the physically significant combinations, namely, the last six, are well determined.

The building loss coefficient obtained from the data was 56.7 Btu/h•F (29.9 W/°C) in run 1 and 57.1 Btu/h•F (30.1 W/°C) from run 2. The equivalent clear aperture area was 17.2 ft^2 (1.6 m^2) in run 1 and 17.5 ft^2 (1.63 m^2) in run 2. Given the 25 ft^2 (2.32 m^2) of double glazing with a transmissivity of about 0.6 and opaque gains, the numbers are reasonable.

The building loss coefficient calculated from a building description is consistent with the value in Table 1. The calculation of the loss coefficient is tedious and somewhat ambiguous because the test cell (constructed a few years earlier for unrelated purposes) has rather complicated construction details. The regressed value is likely to be more reliable than the calculated value. This demonstrates another important point: for buildings with unknown (or uncertain) material properties and complicated construction details, simulations based on detailed inputs may be unreliable. On the other hand, performance data implicitly contain all the complexities. Building parameters obtained from performance data provide reliable inputs to a BEVA simulation (Subbarao 1984; Subbarao, forthcoming).

The values of W/V and $-\phi_v - \phi_w$ in Table 1 tell us that if the outdoor temperature swings by 20 F at the diurnal frequency, then the indoor temperature swings by 9 F with a lag of 3^h05^m according to run 1. The values of S/V and $-\phi_s - \phi_v$ tell us that if the solar radiation swings by 50 Btu/h•ft^2 at the diurnal frequency, then the indoor temperature swings by 6.5 F with a time lag of 4^h11^m according to run 1. These numbers include the effect of all the thermal masses in the building. To determine the building performance under actual weather and internal gains, we have to combine the effects of various driving functions at various frequencies, which is actually quite simple (Subbarao 1984).

In Table 1 the same data were used for the two runs. We determined the physically significant building parameters reasonably well. We considered data from different periods to determine if the same building parameters were obtained from different periods. This indeed turns out to be the case (Subbarao et al., forthcoming). Applications to a passive residential building and to multizone buildings are given in Subbarao (1984; forthcoming). Retrofit performance analysis by this method is given in Subbarao et al. (forthcoming). Extensions to include nonlinearities, such as variable infiltration and interzone airflows, are given in Subbarao (1984; forthcoming). One can easily derive relations between the parameters defined in this paper and the time constant for cool-down tests.

CONCLUSIONS

The test cell results clearly demonstrate that the building parameters are physically meaningful quantities and that they can be determined from short-term tests. Two significant developments are needed before this method can be routinely used: (1) short-term test protocol for a variety of buildings to estimate building parameters with small enough errors, and (2) a method to deal adequately with seasonal variations of solar parameters. Work is underway to develop them.

This study of building parameters is part of a project whose goal is to perform building diagnostics to reconcile the differences between design and actual performance, to analyze retrofits with measurement-based building parameters, and to determine long-term performance from short-term tests.

NOMENCLATURE

a	Regression coefficients
L	Building loss coefficient
n,k	Integers

N	Integer related to number of terms in the regression equation
$Q_{aux}(t)$, $Q_{aux}(k)$	Auxiliary heat input
$Q_{int}(t)$, $Q_{int}(k)$	Internal gains
$Q_{sun}(t)$, $Q_{sun}(k)$	Solar flux on a reference orientation
So	Equivalent clear aperture area
$\vec{S}$ (S,ϕ_s)	Vector (magnitude S, phase ϕ_s) representing heat flows in response to solar flux
t_{lag}	Time lag between cause and effect
$T_{in}(k)$	Average inside air temperature between times $(k-1)\delta$ and $k\delta$. (k is an integer.)
$T_{in}(t)$	Inside air temperature at time t
$T_{out}(t)$, $T_{out}(k)$	Outside air temperature
$\vec{V}$ (V,ϕ_v)	Vector (magnitude V, phase ϕ_v) representing index temperature response to auxiliary heat input
$\vec{W}$ (W,ϕ_w)	Vector (magnitude W, phase ϕ_w) representing heat flows in response to outside temperature
δ	Time increment of discrete data
γ,ϕ	Magnitude and phase of certain intermediate quantities
τ	Period of sine wave

Superscript

$\bar{}$	Average values

Subscript

aux	Auxiliary heat input
in	Indoor air
int	Internal. gains
out	Outdoor air
sun	Solar radiation

ACKNOWLEDGMENT

This work was supported by the U.S. Department of Energy, Passive and Hybrid Solar Energy Division of the Office of Solar Heat Technology.

REFERENCES

Kusuda, T. 1982. A Comprehensive Variable-Base Degree-Day Method for Simplified Residential Energy Analysis. National Bureau of Standards, Washington, DC.

Fels, M. 1984 (Mar.). The Princeton Scorekeeping Method: An Introduction. PU/CESS Report 163.

Solar Energy Research Institute. 1983. Passive Solar Performance: Summary of 1981-1982 Class B Results. SERI/SP-281-1847. SERI, Golden, CO.

Subbarao, K. 1984. BEVA (Building Element Vector Analysis): A New Hour-by-Hour Building Energy Simulation With System Parameters as Inputs. SERI/TR-254-2195. Solar Energy Research Institute, Golden, CO.

Subbarao, K. Forthcoming. Thermal Parameters for Single and Multizone Buildings and Their Determination from Performance Data. SERI/TR-253-2617. Solar Energy Research Institute, Golden, CO.

Subbarao, K., et al. Forthcoming. Short Term Tests for the Determination of Envelope Retrofit Performance. SERI/TP-253-2639. Solar Energy Research Institute, Golden, CO.

Table 1.
Regression Coefficients and Building Parameters for a Test Cell*

	Run 1	Run 2
N_{in}	1	2
N_{out}	1	1
N_{sun}	1	2
N_{aux}	0	2
a_k^{in} $k=0,\ldots,N_{in}$	1.00, -0.941	1.00, -1.392, 0.421
a_k^{out} $k=0,\ldots,N_{out}$	0.184, -0.124	0.104, -0.0744
a_k^{sun} $k=0,\ldots,N_{sun}$	0.0141, 0.0040	0.0171, 0.00807, -0.0162
a_k^{aux} $k=0,\ldots,N_{aux}$	0.00106	0.00203, -0.00164, 0.00013
L [Btu/h•F (W/^{o}C)]	56.7 (29.9)	57.1 (30.1)
S_o [ft^2 (m^2)]	17.2 (1.60)	17.5 (1.63)
W/V	0.450	0.408
$-\phi_w - \phi_v$	$-46.2^o = -3^h05^m$	$-51.7^o = -3^h27^m$
S/V [F/(Btu/h•ft^2)] [^{o}C/(W/m^2)]	0.129 (0.0227)	0.129 (0.0227)
$-\phi_s - \phi_v$	$-62.7^o = -4^h11^m$	$-51.4^o = -3^h26^m$

*The same performance data are used for runs 1 and 2; the only difference is in the number of regression coefficients. While the individual regression coefficients are hard to interpret, note how the physically significant parameters (the last six rows) are reasonably well determined. The last four rows refer to building response at the diurnal frequency. See the text for a discussion of their significance.

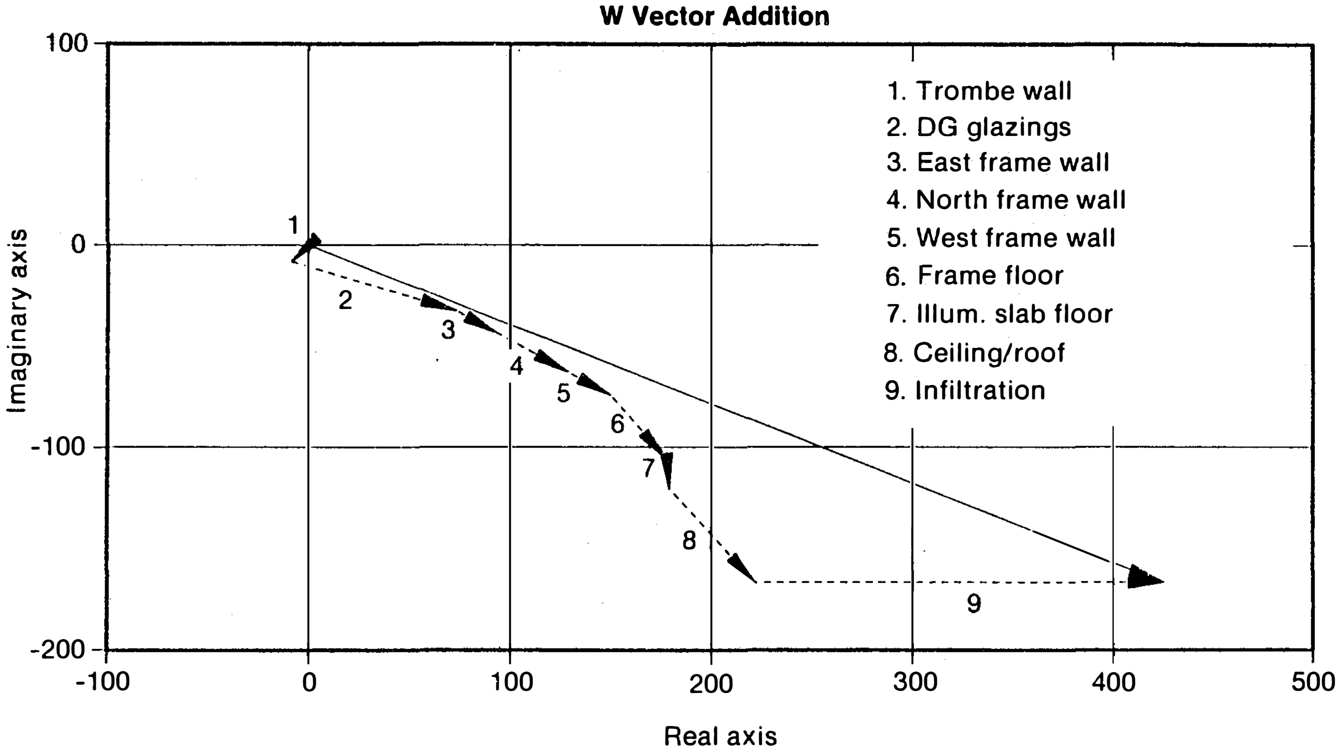

Figure 1. A Calculation of the W Vector Representing the Total Building Response to Outdoor Temperature Fluctuations as an Element-by-Element Sum of Individual Vectors Representing the Response of Each Element. The example building comprises the components listed in the figure.