DEVELOPMENT OF SIMPLIFIED DESIGN TOOLS USING A NEW APPROACH TO BUILDING ENERGY SIMULATIONS

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ABSTRACT - Anew approach to the use of building energy simulations for simplified design tool development is presented. The method which can be described as a form of "computational synergetics," uses simulations for pattern recognition, functionalizing terms in analytic equations, and analysis of climatic data. Many existing design tools have been developed using correlation approaches that provide relatively limited information for rather large computational efforts. Correlations can frequently obscure fundamental physics as well. The presented method employs correlations in a minimal sense while maintaining clarity in the physics of building energy response. A total of only 925 simulations are required to develop generalized heating and cooling energy balance equations for the entire U.S. while other methods which are correlation intensive require thousands or tens of thousands of simulations, often with less resulting generality.

INTRODUCTION

The advent of the modern day computer and building energy analysis simulations has significantly advanced the understanding of building energy performance. Where before buildings were treated in static, steady state terms, we can now view them as interactive, dynamic systems. The limits imposed by our ability to compute or to accurately measure were lifted by a powerful new research method. No longer was one restricted to simplified heat flow equations solvable without computers, one could overwhelm the problem through the numerical calculation of systems of nonlinear equations made possible by the computer. Slow, laborious physical experiments were complemented by the use of simulation as a computational experiment in which one could quickly see the sensitivity of parameter variation and gain insight into building thermal processes.

In this paper we address the issue of, assuming the availability of credible building energy analysis simulations, how can they be used more effectively to gain insight into building energy performance and thus provide "tools" for building energy design. Our primary concern is the appropriate and effective use of building energy analysis simulation for simplified design tool development. It is our belief that many researchers and practitioners in the field have used simulations for brute force numerical calculation without fully recognizing their value for pattern recognition, climatic data processing, and analytic equation development. All three are invaluable components in building energy research and design tool development.

In this paper we restrict ourselves to residential and light commercial buildings in which the mechanical system behavior is not the dominant issue. We feel that simulations should apply directly as a design tool for system-dominated buildings only, otherwise their purpose should be for the development of the appropriate, simplified design tool.

We define a design tool as the combination of: 1) design guidelines which funnel the user to the; 2) calculation procedure which serves as a final verification (see Fig. 1). We insist that "what if" processes done primarily with a calculation procedure are inefficient, revealing insights only slowly and expensively. The role of simulations is to produce universal and location-specific guidelines of such useful quality that the number of iterations through a calculation procedure is minimal. A limit of one or two passes is a worthwhile goal.

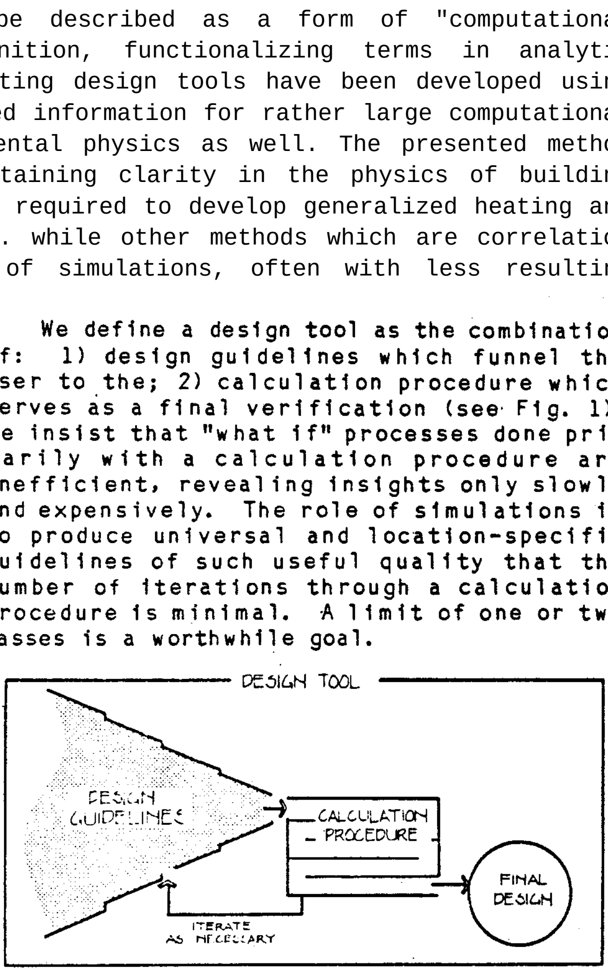

Fig. 1. Design Tool is Comprised of Design Guidelines and Calculation Procedure.

The achievement of a successful design tool, whether manual or computerized, is a matter of producing the right amount of simplicity, without sacrificing accuracy, and providing the user with valuable insights and directions during the design process. There are certain philosophies we've embraced in our experience in building energy research and design tool development:

(1) We approach the use of correlations cautiously, feeling they often lead to restricted usefulness while simultaneously limiting insight into thermal behavior by hiding fundamental physics under a veil of statistics. We disagree with the correlation approaches of Sullivan and Selkowitz (1) and Balcomb, et. al. (2) which in our view require

far too many simulation runs to attain rather few useful bits of information. A recent article by Lunde (3) supports our view.

It is important, in our opinion, to retain a first principles perspective and understanding of thermal mechanisms and reflect this perspective and understanding in a building energy design tool. In developing design tools we examine the thermal details of building components and component interactions to attain a composite understanding of whole building thermal performance. We identify and elucidate both universal and climate specific patterns and guidelines. We use correlations in a minimal sense and only when physical meaning is clarified or at least not obscured. Physical meaning must remain clear to both the researcher and design tool user.

(2) We feel that balanced heating and cooling design, a long neglected issue until only recently, is crucial and leads to choices in conservation and passive solar measures unpredicted by heating considerations alone (4, 5, 6). In our opinion, the early emphasis on heating has led to many poor and expensive passive building designs. It seems shameful that because of lack of vision the building energy research community is now faced with a game of "catch up."

(3) We embrace the emerging paradigm of "computational synergetics" (7) in which computation, analytic methods, and graphic visualization combine to provide the researcher with a most formidable set of tools.

The main focus of this paper is to introduce our particular blend of "computational synergetics," to elaborate on our minimal-correlation approach to building energy design tool development, and show how a simulation can be viewed as an analytic tool in processing weather data. We seek to lend power and elegance to building energy simulations.

COMPUTATIONAL SYNERGETICS

The development of simplified building energy design tools is based on a form of "computational synergetics" which comprises elements of: a) pattern recognition, primarily through graphic visualization of simulation outputs; b) analytics in which specific terms are functionalized through simulation; and c) climatic data analysis using simulations as an analytic tool. We will present examples of these topics to elucidate our method.

Pattern Recognition

Graphic visualization using key simulation outputs has served as an invaluable component in building energy design tool development. The process of pattern recognition through graphic visualization is described with three examples:

1) Building energy load curves for heating and cooling at incremental thermal mass levels has revealed patterns of performance (see Figs. 2 and 3) that led to the creation of mass scaling factors. These features are nearly universal, applying to all climate regions, and are weakly affected by building characteristics such as the BLC (Building Load Coefficient) for meaningful ranges of passive solar aperture area. They break down at low and high levels of glazing where added mass is unnecessary and where overheating occurs, respectively.

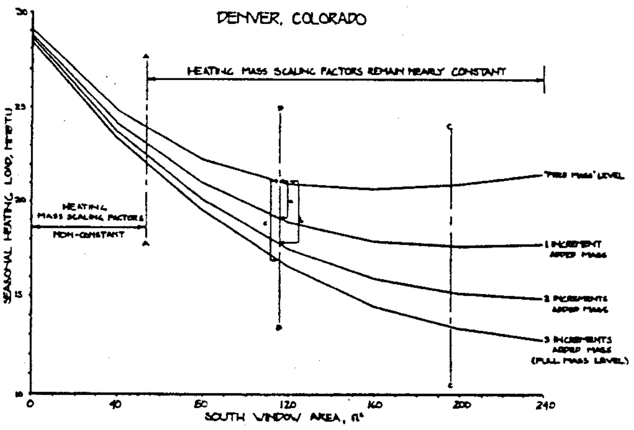

Fig. 2. Pattern Recognition of Thermal Mass Effects for Heating.

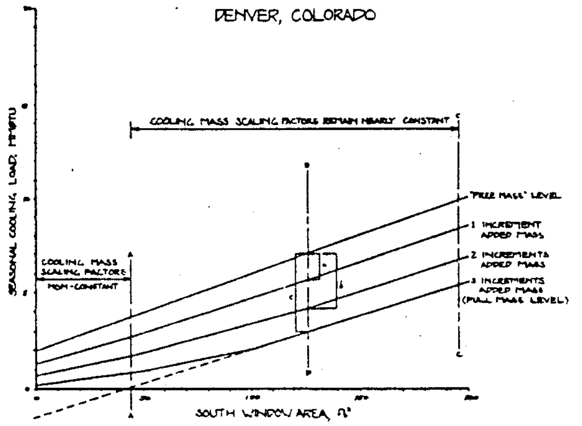

Fig. 3. Pattern Recognition of Thermal Mass Effects for Cooling.

The usefulness of the mass scaling factors is that once building energy performance is determined from simulation for arbitrary limits of low and high mass, the performance can be determined for all intermediate mass levels by simple scaling (see Fig. 4 and 5). Typically the lower mass limit is chosen as either zero or the "free mass" (intrinsic mass due to drywall, furniture, etc.) level of a chosen architectural style, and the high mass limit corresponds to the maximum added thermal mass as constrained by geometry. The mass limits are chosen for convenience and greatest range of applicability. That the mass scaling factors apply between arbitrary mass limits is beyond the scope of this paper. The reader is referred to reference 8 in which the development and use of mass scaling factors are described for heating and cooling calculations.

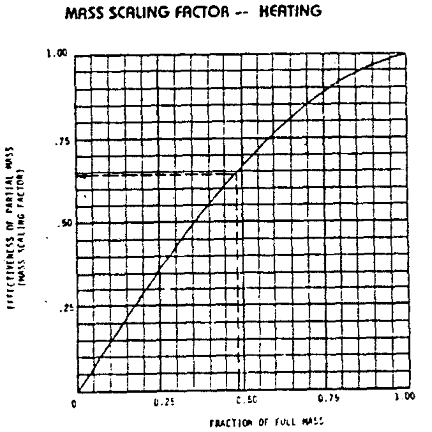

Fig. 4. Mass Scaling Factor - Heating.

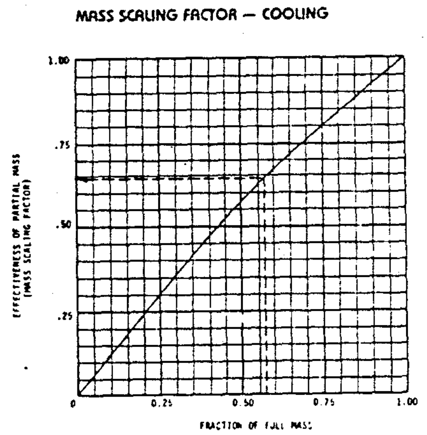

Fig. 5. Mass Scaling Factor - Cooling.

2) An examination of heating load curves and venting requirements to prevent indoor temperatures from exceeding an upper limit (heating setpoint is typically 68°F with a vent point of 78°F) reveals some interesting patterns of practical design use (see Fig. 6 for heating and venting load curves as a function of double pane passive collector area). If we evaluate the ratio

$$[\partial H_{HS}/\partial A_c] / [\partial V_{HS}/\partial A_c] \qquad [1]$$

where: H_{HS}, heating during heating season

V_{HS}, venting during heating season

A_c, passive solar collector area

as a function of A_c we see a diminishing return on the passive solar productivity of increasing aperture area vs. the tendency of the building to overheat (Fig. 7). V_{HS} climbs at such a high rate beyond a certain value of A_c that indoor temperature control becomes a non-trivial issue. In practice overglazed buildings will lead people to either pull their curtains or open their windows and leave them in that state such that the effectiveness of the passive solar design is lost. Smart control strategies to handle venting are not prevalent in current designs. Fig. 7 shows that moderate aperture areas to the left of the minimum point of the H_{HS} curve in Fig. 6 are probably more appropriate than the aperture area corresponding to the minimum. Improved glazing systems, e.g., superglazing with high solar transmissivity and high thermal resistance, do increase passive productivity as shown in Fig. 7. However, the usual practice of glazing according to the heating load curve minimum is not a good one due to winter overheating issues and can lead to considerable summer overheating as well.

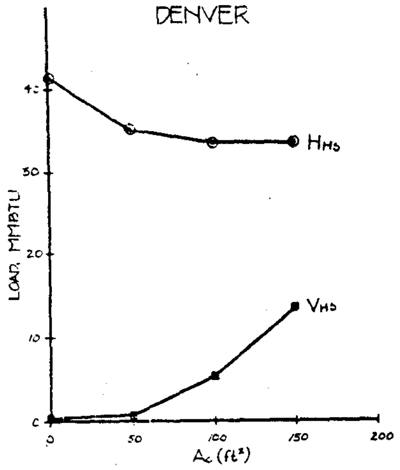

Fig. 6. Heating and Venting Load Curves for Denver.

3) The visualization of cooling load curves reveals a remarkable linearity independent of BLC that has led to the development of a simplified cooling calculation procedure (5). Figures 8, 9, and 10 show cooling load curves for Miami and Phoenix at light and heavy mass levels and various setpoint temperatures. A breakdown of sensible and latent cooling loads are reflected for Miami. Here we only indicate the utility of visualization with regard to building cooling energy performance. An expanded treatment is given in Ref. 5.

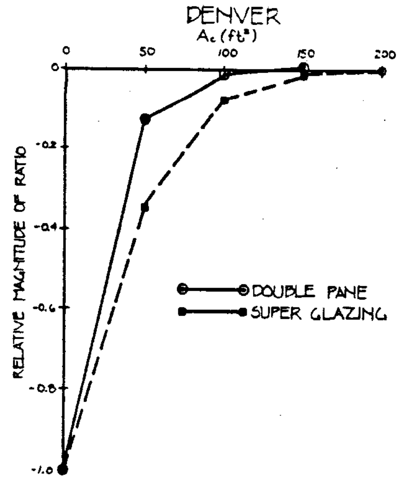

Fig. 7. Ratio of $\partial H_{HS}/\partial A_c / \partial V_{HS}/\partial A_c$

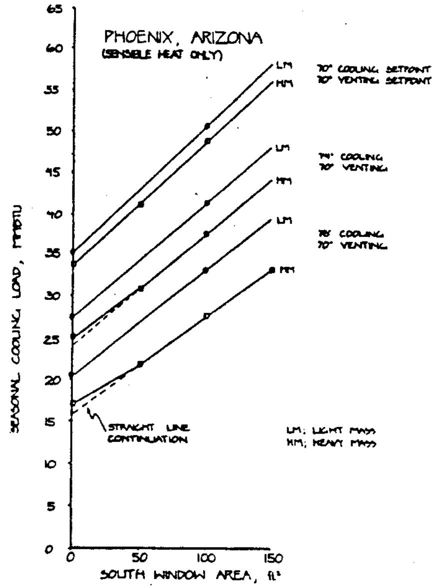

Fig. 8. Seasonal Cooling Load Curves for Phoenix.

Simulation as Numerical Processor for Analytic Equation Development

In this section we introduce the notion that simulations can economically be used to produce functional values of key terms in analytic equations for predicing building energy performance. Excessive numbers of correlations are unnecessary. The resulting equations are general and can be used to perform parametric analysis for developing design guidelines and calculation procedures or can be used directly as calculation procedures themselves if programmed for a microprocessor or certain programmable calculators. The power of the analytic equations is that they essentially have the same capability in determining energy performance with nearly the same accuracy as a simulation. The only limitation of the analytic equations is the embedded range of applicability of the terms as functionalized by simulations. Our experience has been that our method has a far broader range of applicability than the available correlation methods and can be produced at a fraction of the computational effort.

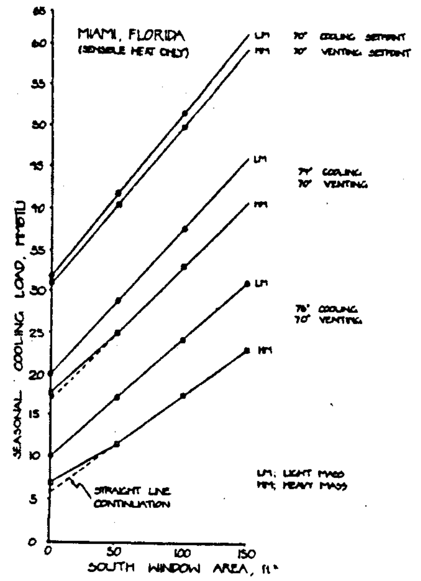

Fig. 9. Seasonal Cooling Load Curves for Miami.

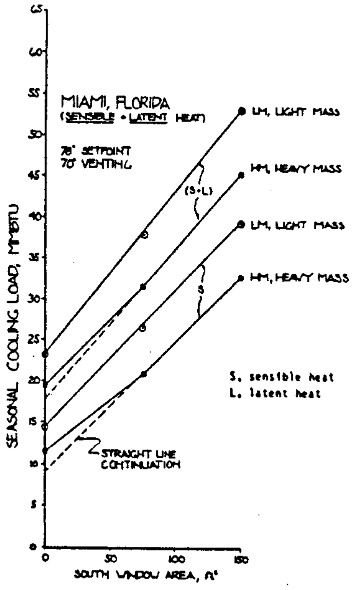

Fig. 10. Seasonal Cooling Load Curves for Miami - Sensible + Latent.

The Generalized Heat Balance Equations for Heating (GHBE-H) are written as

$$Q_H = Q_{H,LM} - f_H \left(\left(BLC_B + 24 \sum (U_{c,i} - U_{w,i}) A_{c,i} \right) \left(n (T_{rm,LM} - T_{rm,HM}) \right) + (V_{H,LM} - V_{H,HM}) \right) \quad [2a]$$

in which

$$Q_{H,LM} = (BLC_B + 24 \sum (U_{ci} - U_{w,i})\ A_{c,i})\ (n(T_{rm,LM} - T_{amb})) - G_s - G_{int} + V_{H,LM} - \sum (R_{o,i}/R_{T,i})\ A_i I_i \propto_i \quad [2b]$$

where:

Q_H is net heating load

$Q_{H,LM}$ is heating load at light mass limit

$Q_{H,HM}$ is heating load at heavy mass limit

f_H is mass scaling factor for heating

BLC_B is base building load coefficient

$U_{c,i}$ is U-value of passive aperture

$U_{w,i}$ is U-value of wall replaced by $A_{c,i}$

$A_{c,i}$ is area of passive aperture (arbitrary orient.)

n is either number of days in each month or entire heating season

$T_{rm,LM}$ is average room temperature at light mass level

$T_{rm,HM}$ is average room temperature at high mass level

T_{amb} is average ambient temperature

$V_{H,LM}$ is vent energy at light mass level

$V_{H,HM}$ is vent energy at high mass level

G_s is solar gain through passive apertures

G_{int} is internal gain

$R_{o,i}$ is outside film coefficient of wall or roof

$R_{T,i}$ is total wall or roof thermal resistance inclusive of inside and outside film coefficients

I_i is orientation-dependent incident solar on wall or roof

$\propto_i$ is solar absorption coefficient of wall or roof

i is subscript corresponding to orientation of each solar aperture, wall, or roof

The passive solar gain term in Equation 2b can be expanded as

$$G_s = \sum (I\ A_c \Upsilon \propto_c (1 + \epsilon))_i \qquad [2c]$$

where:

Υ is solar transmissivity

$\propto_c$ is room cavity absorptance

ϵ is fraction corresponding to net useful heat due to solar energy absorbed by glass ; $\epsilon = 0.06 - 0.07$

Equations 2a, 2b, and 2c can apply to either a monthly or seasonal time frame. Most of our applications pertain to a seasonal span. Input parameters include user-supplied building descriptions and location-specific climatic data.

The terms V_H and T_{rm} are functionalized by simulations for light and heavy mass limits and, in a strict sense, are correlation-based. However, they require far fewer simulations than the usual correlation methods employed in building energy design tool development and their usefulness is expanded by climate similarity analysis (shown later). Approximately 36 simulations are required to functionalize V_H and T_{rm} for each heating climate region. By similarity analysis there are 15 climate regions in the U.S., so a total of only 540 simulations are required to address the entire country.

Equations 2a, b, c require no baseline building and can handle arbitrary inputs of thermal mass, glazing type and orientation, insulation, and heating setpoint. (The use of night insulation is included as an additional term in other of our efforts (6) but is omitted here.) Efforts by others (1, 2) can make no such claims of ease of development and use. We make the additional claim that our balance equations maintain a readily apparent physical interpretation. Furthermore, the choice of a monthly vs. a seasonal time frame in functionalizing the appropriate terms in the balance equations entails no additional simulations and only a moderate difference in preparation. A monthly-based balance equation, programmed for a microcomputer, would, of course, run longer than its seasonal counterpart.

The terms V_H and T_{rm} are functions of solar and internal gains, mass level, BLC, heating setpoint, and vent point and are determined by systematic simulations. Details of their development and functional form are beyond the scope of this paper, however.

The Generalized Heat Balance Equations for Cooling (GHBE-C) are expressed as

$$Q_C = Q_{BC} - f_C\ (b_{LM} - b_{HM}) + ((1 - f_C)\ m_{LM} + f_C\ m_{HM})(G_s + 1/2\ G_{int}) + ((1 - f_C)\ a_{LM} + f_C\ a_{HM})\ 1/2\ G_{int} \qquad [3a]$$

in which

$$Q_{BC} = \sum (24n\ (T_{amb} - T_{rm}) + R_o\ I \propto)\ A_i / R_{Ti}$$
$$+ 24\ n \rho C_p\ (T_{amb} - T_{rm})\ (V\ ACH)$$
$$+ Q_H - Q_V + Q_L \qquad [3b]$$

where:

Q_c	is net cooling load
Q_{BC}	is base cooling load (without G_s and G_{int})
f_c	is mass scaling factor for cooling
a_{LM}, a_{HM}	are coefficients corresponding to internal gains for light and heavy mass limits
b_{LM}, b_{HM}	are coefficients corresponding to the cooling load in the absence of solar and internal gains for light and heavy mass limits
m_{LM}, m_{HM}	are the BLC-independent slopes of the cooling load curves for light and heavy mass limits
n	is either number of days in each month or entire cooling season
ρ	is air density
C_p	is heat capacitance of air at constant pressure
V	is building volume
ACH	is building air change rate due to infiltration

and the following terms correspond only to the base cooling load, Q_{BC} (Equation 3b), in which solar and internal gains are zero:

Q_H	is incidental night time heating load during cooling season
Q_V	is venting energy
Q_L	is latent cooling load

Other terms are as previously defined except that they pertain to the cooling season.

An in depth explanation of Equations 3a, b can be found in Ref. 5. Their empirical nature, based on simulation results, is more subtle than for Equations 2a, b, c and detailed discussion of them is beyond the scope of this paper. A few additional elements will be presented, however.

Simulations indicate that the term T_{amb} - T, appearing in the base cooling load, Q_{BC} essentially independent of BLC, and can be treated as a constant for each cooling set point temperature on a location-specific basis. Cooling climate similarity analysis extends the usefulness of the preceeding fact. Similarly, the difference $Q_H - Q_V$ has all the properties of the term $T_{amb} - T_{rm}$. The term Q_L is a function of ACH and Q_{BC}, ignoring the term Q_L.

The empirical coefficients and additional terms in Equations 3a, can be determined with 33 simulations for each cooling climate region. There are 11 cooling climate regions in the country according to climate similarity analysis, and therefore a total of 363 simulations are required to handle the whole U.S. The resulting utility, as for the balance equations for heating, is to be able to manage arbitrary inputs for a variety of building parameters, solar and internal gains, and cooling set point temperatures.

Ventilation cooling is incorporated in the GHBE-C to minimize the mechanical cooling load. Although, it is not a recommended design practice, the ability to turn off the ventilation is permitted in order to assess the effectiveness of a ventilation strategy. This feature is incorporated into the GHBE-C for the whole nation with an additional 22 simulations, making a grand total of 385 simulations for the GHBE-C.

In summary a total of only 925 simulations are required to develop the GHBE-H and GHBE-C for the entire U.S. Contrast this with Ref. 1 in which 3,400 simulations were employeed to develop correlation equations that handle far fewer building input parameters than do the GHBE-H and GHBE-C, and for only two cities. Most other methods, which are primarily correlation-intensive, require thousands or tens of thousands of simulations to treat the entire U.S. and for only a limited range of building parameter variations compared to the GHBE-H and GHBE-C.

<u>Simulations as Analytic Tool in Climate Data Processing</u>

The utility of the GHBE-H and GHBE-C described in the preceeding section is extended by a method of climate similarity analysis in which the entire U.S. is divided into heating and cooling regions. As previously discussed, there are 15 heating and 11 cooling climate regions. Each region is represented by a single city such that the GHBE-H and GHBE-C, once their key terms are established through simulations for each climatic region, are then used to perform parametric analysis of the representative cities. Results of each representative city are then applied to all remaining cities in each climatic region by a simple scaling procedure. We would like to stress that it is convenient and useful to divide regions on the basis of heating and cooling, separately, as opposed to the method of Andersson et. al. (9) in which the seasons are lumped to establish a single similarity parameter.

Climate similarity for heating is determined by a two-step process: 1) A Climate Analysis Program (CAP), developed by Architectural Energy Corporation, directly assesses the Typical Meteorological Year (TMY) weather files for each U.S. city to evaluate certain key parameters and ratios. For heating, an important ratio for similarity is

$$HDD/VS \qquad [4a]$$

where:

HDD is heating degree days to some temperature base

VS is incident solar flux on a south facing vertical plane

This ratio is evaluated over the entire heating season of each city, then normalzied on the basis of each location's season length for integration, plotting, and comparison to other cities. Fig. 11 shows the various heating climate regions determined by this process; 2) Apparent similarity is determined by the previous step. It is now necessary to run two simulations for each city to confirm actual similarity since the bulk parameter HDD/VS can misrepresent the underlying weather variations occurring on small time scales. The two simulations for each city conserve two parameters for each apparently similar city

$$BLC \cdot HDD = C_1 \qquad [4b]$$

$$A_c \cdot VS = C_2 \qquad [4c]$$

in which C_1 and C_2 are region-specific constants. Of the two simulations, one corresponds to $A_c = 0$ and the other to $A_c = C_2/VS$, where VS is specific to each city. If the slopes of the heating load curves resulting from the simulations are nearly equal, then two cities are actually similar.

The proceeding two-step process leads to the definition of subregions of several of the initially defined regions, primarily those in southern latitudes. The original 11 regions as shown in Fig. 11 are expanded to 15. Figs. 12 and 13 show three similar cities from one of the heating climate regions.

Climate similarity for cooling presently is based strictly on simulations. Since cooling load curves are linear and the parameter M_{LM} for each city is indepdendent of BLC, M_{LM} becomes the basis for assessment of similarity between cities. The values of M_{LM} are computed from two simulations for each city. If two cities have nearly equal values of M_{LM}, they are similar. The issue of sensible vs. latent cooling components are addressed by reviewing these components directly from simulation outputs. Values of M_{LM} are based on total cooling loads. Cities that are similar on the basis of M_{LM} values, but have different latent to sensible cooling fractions, are treated separately only in the Q_L term of Equation 3b. Cooling similarity regions do not contour as conveniently as heating regions and are therefore not shown.

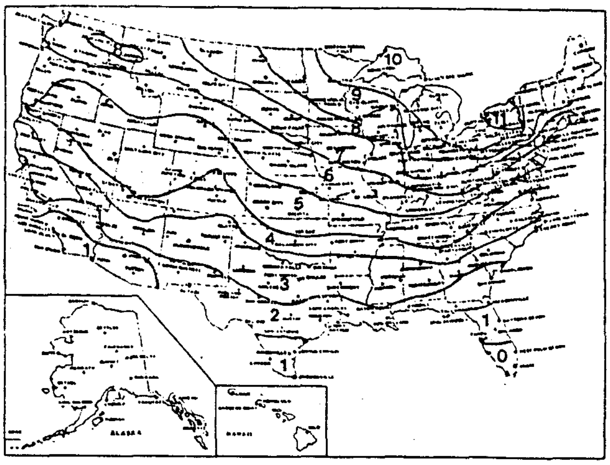

Fig. 11. Heating Climate Regions by Similarity.

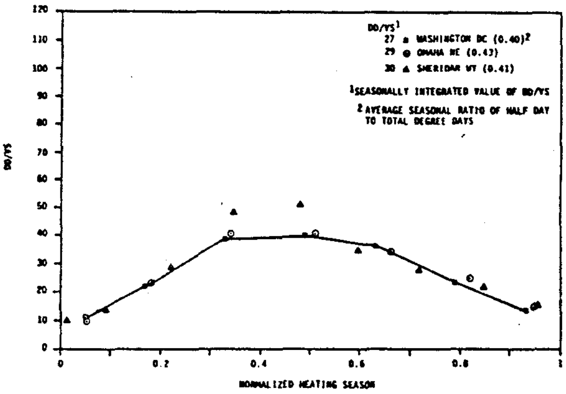

Fig. 12. Similarity Variable HDD/VS for Heating.

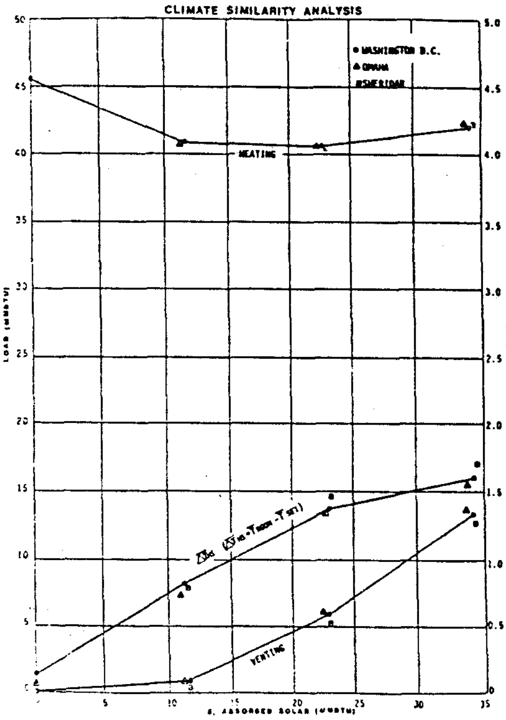

Fig. 13. Heating Load Curve, V_{HS}, and ΔT_{HS} for Three Similar Cities.

Because of the way simulations play a role in refining heating similarity and totally define cooling similarity, they can be viewed as an "extended analytic tool" in which they act as analytic processors of climatic data. As such they are not weaker or less elegant than what are thought of as conventional analytic techniques, but are every bit as valid and in some cases a more powerful approach.

CONCLUSIONS

We have introduced our approach to "computational synergetics" for building energy research and simplified design tool development. Our method uses simulations for pattern recognition of building energy processes, functionalizing of key terms in analytic energy balance equations, and "extended analytic" climatic data processing. We are able to develop generalized energy balance equations for heating and cooling of a wide range of building parameters for the entire U.S. with only 925 simulations. Our method stresses a minimal correlation approach to building energy analysis. Typical correlation - intensive methods for analysis and design tool development require thousands or tens of thousands of simulations with relatively limited ultimate capability.

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