MACRODYNAMICS: A UNIFIED FRAMEWORK FOR BUILDING ENERGY ANALYSIS

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ABSTRACT-Dynamic building thermal models are needed in design and monitoring applications for low-energy, innovative buildings, and can be classified as "microdynamic" or "macrodynamic". The basic concept of a microdynamic simulation (e.g., DOE2.1, BLAST3) Is that given a "microscopic" description of the building (material properties, detailed geometry, etc.), one can, by using known laws of nature, determine the building performance by simulating all energy fluxes in each element in the description. Advantages of this approach include potential generality and its ability to handle nonlinear models. However, the difficulty in obtaining the necessary inputs and the often uncertain nature of various approximations to basic laws makes use of the simulations In monitoring applications cumbersome or impossible. A different premise for simulations IS macrodynamics: a building is an aggregated unit whose response to its driving functions can be characterized with only a few, aggregated parameters (macrodynamic parameters such as the well-known building load coefficient). A simulation that uses such parameters as inputs has been described previously (BEVA). For design, when only a detailed building description is available, the macrodynamic parameters can be calculated. On the other hand, performance data on an existing building implicitly contain information on these macrodynamic parameters. Performance monitoring in the form of short-term, whole-building tests provides a method to directly measure the building parameters. Thus, for an existing building, the building parameters can be obtained either by calculation or measurement, allowing data and theory to be balanced for the present application. Potential applications opened up with macrodynamics, as well as practical difficulties to be overcome in realizing this potential are discussed.

INTRODUCTION

There are many uses for building thermal models. For design, simulation provides a means of assessing the performance of different hypothetical building configurations. In addition to design, models are also used in monitoring applications, in which the model is used to interpret and extrapolate the performance of an existing building. Some examples of monitoring problems include: 1) reconciliation of design versus actual performance; 2) retrofit analysis; 3) dynamic component testing; 4) measurement-based energy ratings; and 5) diagnosis of malfunctioning shell or mechanical equipment. In choosing the models and data to meet such diverse needs, it is important to consider the level of detail and accuracy required by the application, carefully balancing what is measured and what is calculated.

Models for building or zone thermal load can be classified based on the level of spatial and temporal detail that are explicitly calculated(1). In this paper we focus on time-resolved or dynamic models, which give performance as a function of time and explicitly account for a wide range of interacting time-dependent processes, such as solar gains, scheduled internal gains, and conduction in walls and storage. Such models are needed for most innovative low-energy designs. For certain applications and when dynamical details are not of interest, time-integrated models (such as variable base degree-day(2)) have proven useful, but they are not discussed further.

Dynamic models can be roughly classified as "macrodynamic" or "microdynamic", depending on spatial resolution of inputs and flux calculations. Microdynamic models resolve a building into all of its spatial components, and require building descriptive inputs for each component of the building. Zone thermal load is calculated by summing each of the component fluxes at each step. Examples include DOE2(3), BLAST3(4), and the bulk of the proposed ENERGY-1(5). Macrodynamic models stem from linearizing a microscopic model, and require inputs that are aggregations of building component properties (e.g., the building load coefficient as a one-time sum over component U-values). At each time step, a macrodynamic model calculates only the total zone dynamic performance (load/temperature).

This paper shows the relative advantages/ disadvantages of two kinds of dynamic models, emphasizing the breadth of applications opened up by the more flexible macrodynamic approach. First, we fully examine the question of aggregation of descriptive parameters, pointing out that a natural heirachy of building thermal parameters exists on material property (most detailed), component, or zone level (most aggregated). For component and zone parameters, they can be measured or calculated from a known set of detailed values. This multi-leveled feature can be fully exploited if the model structure allows entering the simulation at any of these levels. Next, we examine the strengths and weaknesses of both the microdynamic and macrodynamic models. In concluding our study some of the applications and steps needed for the implementation of macrodynamic approaches are stated.

LEVELS OF AGGREGATION

Descriptive parameters of a building exist on three increasingly-aggregated levels: 1) material properties, such as conductivity, specific heat, index of refraction, which must be accompanied by relevant geometry of all materials; 2) component parameters, such as the U-value of a wall, or the net transmission of a glazing; and 3) zone parameters, such as the load coefficient and effective solar aperture area. It is useful to define these levels, because the parameters can both be: 1) directly measured; or 2) for component and zone parameters, calculated from the next detailed set of parameters, if these more detailed parameters are known or simply assumed, as in the design.

Measurement subsumes many details not of direct interest into measured aggregated descriptive parameters. This is true on both component and zone levels. Wall component parameters such as value, measured with standardized tests, are all [illegible] needs to know to accurately compute component fluxes. While a comparison between measured and calculated values helps in understanding wall details (e.g., multi-dimensional and bridging affects), the measured values subsume the wall details and can be used directly. Similarly, zone parameters can be measured by suitable short-term tests. In general, required measurements for determining zone parameters depend both on the particular system and upon the macrodynamic model to be used(1). Zone parameters will depend on many unknown details, such as convective coupling to closets and around furniture, solar irradiance in occupied and hence "cluttered" zones, etc. The measured values subsume these details, which are usually of no direct interest.

The idea of macroscopic parameters as aggregates of microscopic details is very common, and it is worth discussing analogies from other fields. In many cases the relationships between these parameter levels can be exactly formulated. For example, the moment of inertia of a solid (macro level) is expressed as a weighted integral over its mass distribution (micro level). The moment of inertia can be calculated from the details if available, or it can be measured directly as the response to torques, obviating the need to know the exact mass distribution. The exact relation that exists between micro and macro levels allows calculation of the change in the moment of inertia for given changes to the object, even though the total mass distribution is not known. In other cases, particularly where a valid, soluble theory does not exist, the relationship between micro and macro levels is empirical and approximate. An example is the flow of air between building zones, or the reaction rate of exploding gases. In these cases, direct measurement on the appropriate macro level is one way to overcome the lack of or difficulty of applying a more basic theory.

Whether a quantity is microscopic or macroscopic depends on the scale of the quantity relative to the desired results of the analysis. Heat capacity of a material, for example, is a macroscopic quantity from the point of view of a solid state scientist, to be calculated from the properties of the constituents of the solid. However, from the point of view of a building analyst wanting total building loads, heat capacity is a microscopic quantity whose measured value is input to a microscopic building model. Similarly, the convective bulk-air coefficient is a macroscopic quantity from the point of view of someone addressing the details of fluid flow, but is a microscopic parameter for component-based building energy simulation.

MICRODYNAMIC SIMULATIONS

The basic premise of microdynamic simulations is that given a detailed microscopic description of the building, one can apply the well-known laws of energy and mass transfer to determine building performance by simulating every mechanism in every component. Microdynamic simulation is essential for research and development needs. A major advantage of microscopic approaches is that for sufficiently simple structures where requisite inputs are known, simplifying assumptions can be either eliminated, minimized, or introduced at will. Microdynamic simulations are thus needed to verify the accuracy of the simplifying assumptions introduced in macrodynamic approaches. Such model-model comparisons, for example, have been performed in testing degree-day models(6) and in determining impact of variable convection coefficients(7).

A major weakness of microdynamic models is that they generally require inputs on the material properties level for all conduction/radiation components. As a result, literally hundreds of numbers are required for description of the entire building, making it essentially impossible to measure the correct values for any given building. Often, the required building description is not available, as in many retrofit problems. Even when a detailed building description is available, one is still forced to input "typical" or "handbook" values, which can have large uncertainty. Even when component measurements are available, they cannot generally be input to the simulation.

Further, the proliferation of parameters is clearly contradictory to providing intuitive guidance to a designer as to how or why the building model performs the way it does. The designer is forced to employ a "trial and error" search in a complex parameter space, changing parameters and re-simulating. It is much more useful to aggregate these hundreds of numbers into a small number of macro-level descriptors whose values govern performance and can be intuitively grasped. A good example is the total building load coefficient, which, for a massless, non-solar building is the sole parameter one needs to predict performance accurately. Indeed, DOE and BLAST both provide the load coefficient for design guidance, but do not use this macro-level parameter in the simulation.

Perhaps the gravamen against microdynamics is that it is at best cumbersome to use these models in monitoring applications, as shown in Fig. 1. Zone-level performance data has only a few degrees of freedom, which describe its aggregated response to temperature, solar radiation, etc. Such routinely available data is clearly insufficient for "measuring" the correct inputs to a microdynamic simulation, which typically has hundreds of degrees of freedom. One is forced to arbitrarily choose which inputs to "adjust" in minimizing the difference between actual and model. Microdynamic parameters will generally affect several of the zone response features. For example, mass conductivity affects not only the zone U-value, but also the storage in thermal mass from overheated periods and from solar. While engineering judgment can somewhat reduce the arbitrariness in adjusting the inputs, we believe it is, in general, not feasible to sequentially adjust micro-level parameters to fit zone temperature/auxiliary data.

The mismatch in degree of freedom between performance data and micro-level inputs shown in Fig. 1 has the additional consequence that has proven impossible in practice to convincingly "validate" microdynamic simulations. Because one is never sure that the inputs correspond to those in the "real building", disagreement between model/data does not indicate model errors. Error limits can be as large as a factor of 2 or as small as 20% in extended validation studies. Similarly, agreement between data and model does not necessarily indicate correct model inputs (due to the possibility of compensating errors). Mechanism level models are validated by comparison with carefully controlled mechanism level experiments(8).

MACRODYNAMIC MODELS

For specificity, we shall base the discussion of macrodynamic models on BEVA (Building Element Vector Analysis (9,10). BEVA makes the assumption that some of the heat transfer processes are linear, i.e., material properties, and surface transfer coefficients are independent of temperature and time. BEVA then aggregates wall layer and surface properties into three relevant transfer functions at zero and diurnal frequency: heat flow at the interior surface in response to outdoor temperature, indoor temperature, and solar radiation. Only eight parameters are required to describe these transfer functions, in most cases (9). Similarly, BEVA aggregates the component transfer functions into similarly-defined zone transfer functions, also needing eight parameters for full characterization. The zone parameters are vector sums of component vectors, weighted to correctly account for geometrically-dependent convection/ radiation splitting (9). Note that a macrodynamic building model, based on input of zone level thermal parameters, can be used not only when zone parameters are known, but also when either material properties or component level parameters are known. The directly used zone parameters are calculated from detailed levels before the simulation begins. The validity of the linearity assumption must be tested against microdynamic models not making such assumptions. Such tests have been and are being done (6,11).

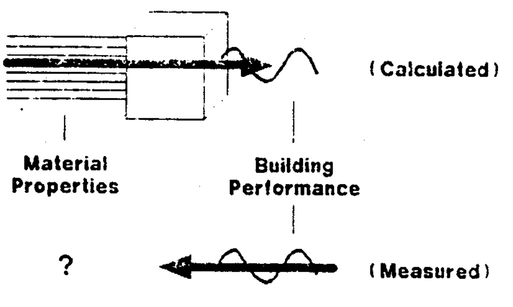

Fig. 1. Schematic of Microdynamic Methods. Building performance is calculated from material properties (upper row) without intermediate access to component or building effective parameters. There is no inverse process to determine inputs from performance data (lower row).

It should be noted that only the linear conduction/radiation aspects are aggregated into the "whole zone" parameters. Non-linear effects or effects of much different time scales (e.g., ground coupling) are easily included in the BEVA framework by explicit calculation, as in microdynamic approaches. Infiltration, for example, could be included in the steady state load coefficient, in an "average value" sense, or it can be explicitly separated and treated by a non-linear model, such as (12). Other effects that are incorporated in the BEVA framework include non-linear air flows between zones, movable insulation, temperature/humidity dependent equipment efficiency models, and mechanical equipment controls (10).

The multi-leveled structure of BEVA is shown in Fig. 2. In this framework, component parameters can be gotten either from material properties and layer description, or directly from hot-box measurement. Similarly, the zone parameters can be either calculated from component values, or can be measured directly from the response of the zone to the various driving forces.

POTENTIALS OF MACRODYNAMICS

For design problems, macrodynamic models offer several advantages over microdynamic approaches. From a computer hardware perspective, a macrodynamic model is generally an order of magnitude quicker to execute, and requires somewhat smaller memory. More importantly, the building parameters form a natural basis for intuitively guiding improvement of the design. A little experience determines what mass-related parameters are required for damping temperature swings. The designer can then quickly iterate the design until the correct parameter values are attained, without the need to explicitly calculate temperature swings.

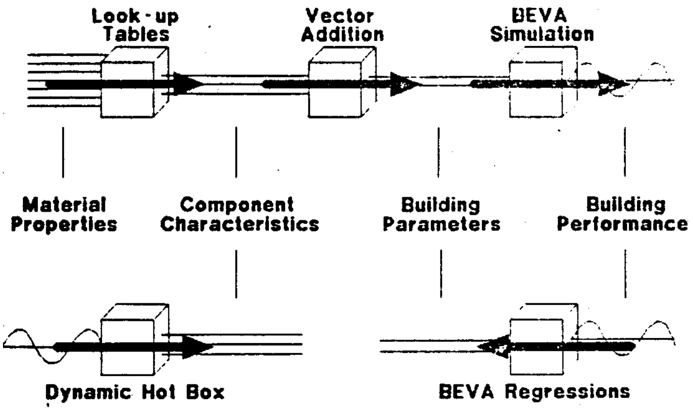

Fig. 2. **Schematic of the BEVA (macrodynamic) Method. Dynamic component and building parameters are available at intermediate points in the calculation (upper row). Component and building parameters can also be determined from measurement (lower row).**

A comparison between microdynamic and macrodynamic approaches to several monitoring problems is shown in Fig. 3. Calculation is shown on the upper row and measurement is on the lower row of each of the small diagrams. For microdynamics, the single arrow on the upper rows shows the jump from materials properties to building rformance. Question marks on the lower rows dicate the lack of unambiguous inverse processes to determine inputs from measurement. For macrodynamics, the multiple arrows across the upper rows indicate the availability of calculated component or building dynamic parameters at intermediate points. Experimentally determined parameters can be compared to calculated results (diamond symbols) or can be used as inputs to the simulation (upward arrows).

Reconciling the differences between expected design performance and the actual performance of the building (Fig. 3a) is another application opened up by macrodynamics. The designer can compare the design parameters to those determined by direct measurement. Disagreement indicates performance differs from design prediction because of construction variance, as opposed to unusual weather or operating schedules differing from those anticipated in the design study.

The most significant advantage of macrodynamic models is in monitoring problems. For retrofit applications (Fig 3b), for example, it is not necessary to have a detailed description of the building. "As operating" zone parameters can be obtained from short-term tests and input to the macrodynamic model for subsequent analysis with standardized weather/internal gains. The most appropriate retrofits are intuitively indicated by "non-optimal" parameter values. Note also that savings from a given retrofit can be quickly rified experimentally, by simulating with rameters as measured with short term tests before and after the retrofit.

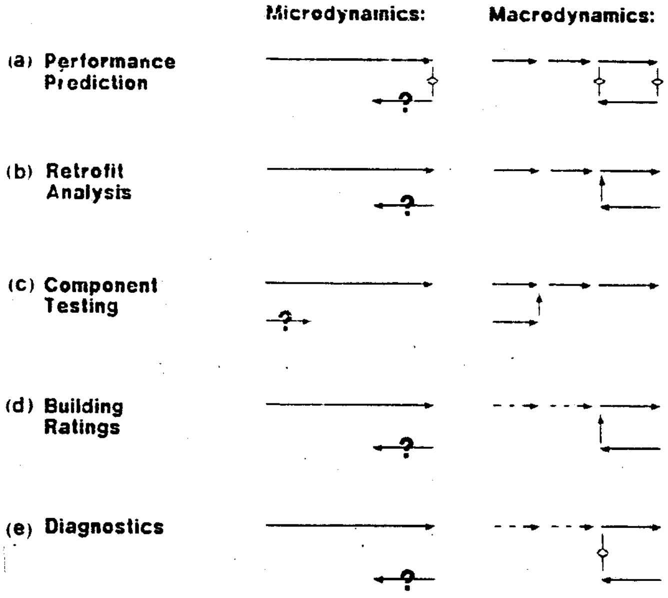

Fig. 3. **Schematic of Microdynamic and Macrodynamic Approaches for Various Applications. Calculation is shown on the upper row and measurement is on the lower row of each of the small diagrams.**

Macrodynamics provides the framework for fully using dynamic component measurements, (Fig. 3c). With microdynamical approaches, one cannot generally input these component measurements directly. For example, this forces the user to externally devise one-dimensional wall conduction layers with fictitious conductivity, specific heat, etc. which will be ultimately "consistent" with the static and dynamic testing results. This is an arbitrary and uncertain process, which of course inhibits development of testing standards and any use of component data. On the other hand, static and dynamic component measurements are an integral (13), natural element of a macrodynamic framework such as BEVA. The measured component transfer functions are directly used to calculate the zone transfer functions.

For maximum credibility, building energy ratings (Fig. 3d) must be based upon measurement, analogous to EPA mileage ratings. A skeptical public will rightfully question ratings based purely on calculation from idealized handbook or typical values as inputs. Macrodynamics, allowing the building parameters to be determined from short-term measurements, is thus a suitable basis for a credible ratings program. The rating (such as expected BTU/year) would be obtained by macrodynamic simulation with the measured zone parameters, long-term typical weather, and a standardized internal gains profile.

Many buildings have or will have energy management systems, which monitor outdoor temperature and radiation, equipment power and fossil fuel utilization, etc. It is clear that these systems can be extended to provide continuous on-line diagnosis of the mechanical equipment performance (Fig. 3e), if zone thermal loads were calculated accurately. A macrodynamic model of the building, with inputs determined from appropriate short-term tests, will provide the needed load information.

Several refinements are needed for the realization of these potentials. First, and most significantly, the errors in regressing macrodynamic parameters from short-term performance data must be made sufficiently small. The errors will be quite large unless the internal gains are suitably varied to bring out clear, unambiguous signals for the related transfer functions(14). A general procedure is being developed for specifying the short-term test protocol, dependent upon the building at hand (zonal structure, mechanical equipment, etc.) Second, models must be developed for calculating the anticipated annual variations in building parameters (such as in the solar parameter) determined from short-term tests. Lastly, in cases where non-linear phenomena such as phase change walls are important, the theory of and software for incorporating such phenomena in macrodynamic approaches needs completion.

SUMMARY AND CONCLUSIONS

Microdynamic models are useful for idealized problems, wherein inputs can be reasonably defined from handbook or typical values. The building energy impact of a variety of non-linear phenomena can be studied in detail, and the effect of simplifying assumptions studied. However, microdynamic models are cumbersome to compare with or to interpret real building performance data. Building parameters must generally be entered at the microlevel, with either component or zone data of little use, in determining suitable modifications to match the existing structure. There is no practical means to measure the requisite inputs.

Macrodynamic models are useful both for idealized design problems and for monitoring problems. For design problems, the building to be built can be described on the thermophysical properties levels or the component level, whichever is most convenient and accurate. In fact, any desired combination of these two descriptor levels allows the aggregated zone parameters to be computed. Furthermore, the computed values of the several zone parameters offer direct, intuitive guidance to designers on why the building model is so performing, and what must be done to improve it.

Most importantly, a macrodynamic model allows the building zone parameters to be regressed from appropriately-specified short term tests. This approach eliminates the myriad of uncertainties and ambiguities which befall microdynamic approaches. As a result, macrodynamics offers a unified, rigorous approach to a great diversity of energy analysis problems. These applications include: 1) determination of why a building performed differently from design expectation, through comparing as-designed and as-measured zone parameters; 2) retrofit engineering and savings prediction, with quick feedback on the actual retrofit impact, if desired; 3) component dynamic testing that can be used directly as inputs to an appropriate macrodynamic simulation; 4) measurement-based energy ratings, with rating indices computed via macrodynamic simulation with parameters determined from short-term test and standardized weather/schedules; 5) continual diagnostics of mechanical equipment, using a macrodynamic model to compute thermal loads.

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