STUDYING ENERGY AND THE BUILDING STOCK: A VISION FOR THE FUTURE

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ABSTRACT

While conducting a study to characterize the energy requirements of the office building stock in the United States, we explored, developed, and tested several nontraditional techniques with potential application to future building stock studies. These approaches involved systematic methods for integrating disparate data sources and automating certain energy modeling functions.

As an outgrowth of this study, we have envisioned a number of new directions and approaches that we believe hold potential for substantially improving the accuracy and efficiency of building energy technologies assessments. Some depend on as-yet-undeveloped capabilities, although we, and other researchers, have conducted prototype efforts that demonstrate their feasibility.

This paper describes these promising directions through comparisons with traditional methods and the methods used in the office building characterization study. Illustrations of potential applications for these improved capabilities are also provided.

INTRODUCTION

The energy bills for the nation's commercial buildings totaled $60 billion in 1986 (EIA 1989). Over the past decade, substantial investments have been made by federal, state, and private organizations (e.g., utilities) in research on energy efficiency in commercial buildings. Significant strides have been made in increasing the energy efficiency of new commercial buildings, and new energy-related technologies promise further improvements in the coming years. The economic and environmental significance of commercial-sector energy use ensures that it will remain an important issue in the future.

Although research on building stock energy efficiency has been substantial, planning and accurate assessment of energy-related research programs remain difficult, problematic, and inconsistent. Reliable performance and impact assessments require that information about the size and composition of the current and projected building stock be brought together with sophisticated engineering analyses. It is inherently difficult to develop information having both the breadth and depth required; information must have the breadth necessary to accurately describe major segments of the building stock, in which new technologies will ultimately be placed, and the depth necessary for detailed studies using energy simulation models. Studies employing end-use metering technologies promise to narrow the range of uncertainty that now exists regarding the actual energy performance of the building stock. However, effective integration of these data sources with energy simulation models — the requisite vehicle for at least the initial stages of these energy-technology assessments — poses major challenges.

The authors have conducted a study designed to characterize the energy requirements of the office building sector for use in targeting research and development of new gas-fueled technologies for a major energy-industry research institute. The study provides information on the current and projected composition of the office building stock and on office building energy requirements and load patterns. Products from this study include a data base of the office building sector, a categorization of that sector, and representative building descriptions for use in building energy simulation.

The study employed a number of nontraditional approaches for compiling information on office stock energy use. The building categories were developed using a statistical technique known as cluster analysis and were designed to represent the entire office building sector with a limited number of categories while reflecting as much of the actual diversity in the building stock as possible. A sample of the office building stock and a variety of other sources were used in developing the building descriptions. Energy simulation results from the building descriptions were calibrated using both metered hourly end-use energy data from a small set of office buildings and annual energy consumption data drawn from billing records for hundreds of office buildings. The data base, representative building descriptions, and building loads have been linked together to increase their ease of use and analytical power.

As a result of the office building study, we have envisioned a number of new approaches that could substantially improve on traditional methods for predicting the impact of energy technologies on actual building populations. The mechanics of conducting building energy simulations are becoming much less onerous due to the development of automated methods and the wider availability of fast computers. New types of investigations are now feasible that even recently would not have even been considered. Some of the envisioned

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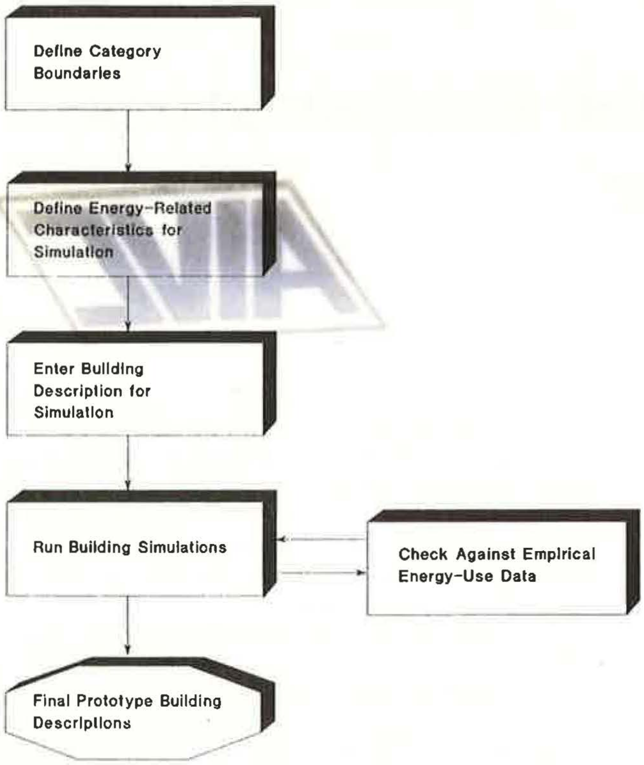

Figure 1 *Traditional process for developing models of the building stock*

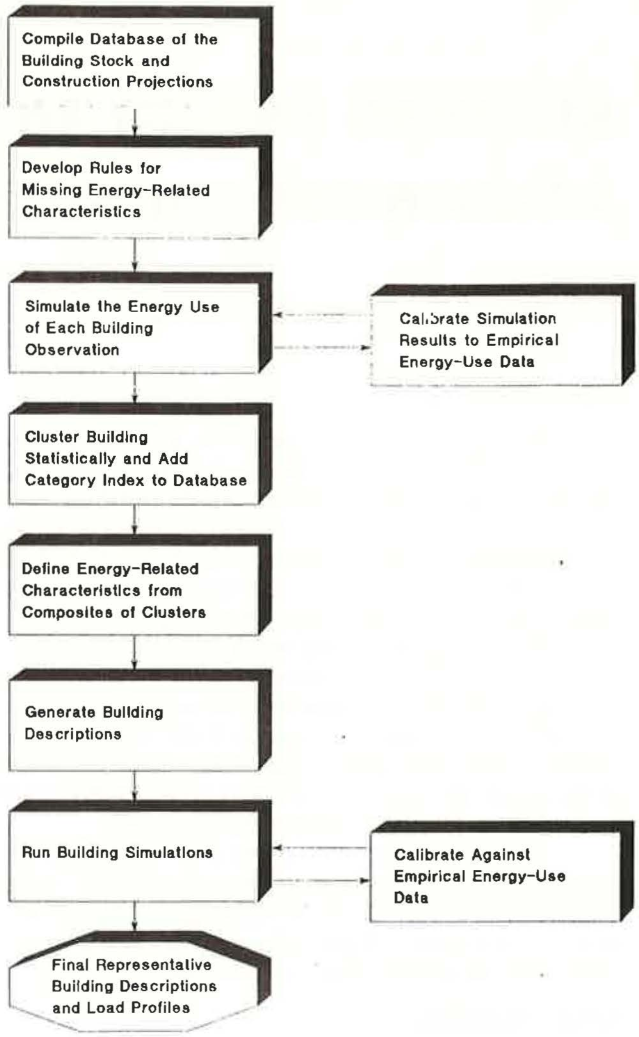

Figure 2 *Process used for developing models of the building stock in the office building characterization study*

approaches depend on as-yet-undeveloped capabilities, although we, and other researchers, have demonstrated their feasibility with partial prototypical systems.

This paper describes the major components of these promising directions in the context of traditional methods and the methods developed for the office building study from which they have evolved. The final section of this paper deals with applications and implications of using these approaches and analytical capabilities to address planning and assessment questions in the future.

COMPARISON OF METHODS FOR MODELING THE BUILDING STOCK

Before evaluating alternative approaches for analyzing energy issues in the building stock, it is instructive to review the methods that have traditionally been used.

The Traditional Process

Figure 1 illustrates the general approach that was often used in the past to model building populations (PNL 1983; McCarthy 1984; Adams et al. 1985; Bergstrom et al. 1985; UIC 1988). Using this general approach, categories are defined for the building stock, most often on the basis of building type, size, and climate. For example, small, medium, and large office buildings would be defined for each of several climatic zones. Category boundaries are defined based on subjective judgment or recognized information sources, such as previous studies characterizing climate. Building descriptions reflecting typical construction practices are defined for each category, based on professional judgment and various published data sources including building codes.

Building descriptors are then transformed into the specific input format required for computer simulation, and the resulting energy performance is compared against empirical building energy-consumption data. Empirical data are primarily used as a check. Attempts to calibrate simulations to empirical data, when performed, have usually been done manually using an iterative process. When complete, the simulations can be used in parametric studies to predict the potential impact of physical and operational changes on the existing building stock.

Process Used for the Office Building Study

In the office building characterization study, a substantially different approach was used, as illustrated in Figure 2. The first step in the process was to prepare a data base of the office building stock. This was done by compiling data from the 1979 Nonresidential Building Energy Consumption Survey (NBECS) (EIA 1981) and proprietary office building construction projections. Data on the 1139 office buildings in the 1979 NBECS are contained in the data base. This information includes both characteristics data (e.g., location, size, age, and physical and operational characteristics) and energy consumption data drawn directly from utility billing records.

The next three steps were designed to subdivide the sector into categories based on how these buildings use energy. If the buildings in the data base could be grouped into categories based on how they use energy, a single building description representing each category could satisfactorily represent that segment of the building population in detailed energy simulation. However, since end-use level data (e.g., heating and cooling) were not part of the energy consumption data in the data base, we had to model the buildings to obtain these breakouts. Without these breakouts, heating-dominated and cooling-dominated buildings with the same energy intensity might be grouped together. While many descriptors necessary for energy simulation were contained in the data base, others were missing, and these had to be supplemented with rules based on published literature and professional judgment. Each observation in the data base was modeled using a program based on a modified bin procedure (Knebel 1983), and key assumptions in the energy model were calibrated so that aggregate results matched the consumption levels from the billing data in the data base reasonably well. The energy model provided a rough approximation of how end-uses break out for each category.

A statistical technique known as cluster analysis was then used to categorize the observations into 20 roughly equally sized groups. This technique generated groups of building observations that maximized within-group similarity based on a set of physical and energy-load characteristics while maximizing between-group differences. In the data base, each of the 1139 office buildings was then assigned to one of these categories (or clusters). The approach is described in detail in a companion paper (Briggs 1990).

Having assembled the data base observations into relatively homogeneous groups of buildings, the next task was to generate building descriptions for use in simulation that would be as representative as possible of each group. We used DOE-2.1D as the energy simulation tool for the final representative building descriptions. Because many of the needed descriptors were contained in the original data base, they were defined for each category simply as the weighted means of those parameters. Simulation input files were created automatically using a program that read values from tables into a base (or shell) input file, thereby completing a direct digital link between the NBECS and the energy simulation model. Where energy-related characteristics were missing, we established rules for defining them, many of which had been developed earlier in the categorization portion of the research.

In the final step, we calibrated the simulations against consumption data for each category using methods that, while systematic, were primarily manual and iterative. The resulting building descriptions are based primarily on survey and empirical data and explicit rules, thus reducing the role of professional judgment relative to previous efforts. Hourly data from the simulations were compiled to provide load profiles for each office building category, a major end product of this study.

Although the process used for developing the representative office buildings is more complex and less intuitive than traditional methods, we believe it has some significant advantages. By basing building categories on differences in both building characteristics and how energy is used, better resolution should be possible with a given number of simulations. Detailed survey and consumption data are systematically incorporated into the building descriptions. Finally, the integration of the data base, representative building descriptions, and load profiles should make the products of this work both easier to use and more powerful. Using the products of this work as an integrated tool was described in Crawley and Huang (1989).

Several drawbacks of the approach should be noted. The approach is technically more difficult both because of its use of specialized expertise in statistics and the frequent need to manipulate large data sets during development. The accuracy of the resulting building stock characterization is limited by the availability and quality of characteristic and energy consumption data. This is not so much a shortcoming of the approach as a facet of the problem, although it largely defines the level of accuracy possible in attempting to characterize building stocks in this way. The data-limitation issue has been addressed in a companion paper (Briggs and Schliesing 1990). Finally, the approach was hampered by limited success and uncertainties in calibration efforts, both in calibrating the energy model for categorization and in calibrating the final representative building descriptions.

Description of Envisioned Method

A process diagram for an approach that would surmount many of these shortcomings is shown in Figure 3. The approach shares a number of features with the method used in the office building study but includes a number of extensions and additional capabilities.

Integration of Construction Projections To assess emerging energy-related technologies, it is necessary to characterize the building stock in which they will be used—future buildings. Obviously, it is difficult to predict the number of buildings that will be built in the future and more difficult still to predict their physical and energy-use characteristics. However, estimating this information is necessary if reasonable assessments are to be made of the potential impacts of long-term research and development programs.

To address this need in the office building study, we developed a characterization of the future building stock using recent NBECS samples, construction projections for office buildings, and information on current trends for energy-related building systems. We assumed that, aside from recognized trends, the distribution of characteristics in the future building stock would resemble those from buildings in the recent past. We used the most recent NBECS as the basis for our future building sample. Each building in the NBECS has a weighting factor indicating the number of buildings that it currently represents in the building stock. By adjusting these weighting factors based on projections of construction activity and estimates of

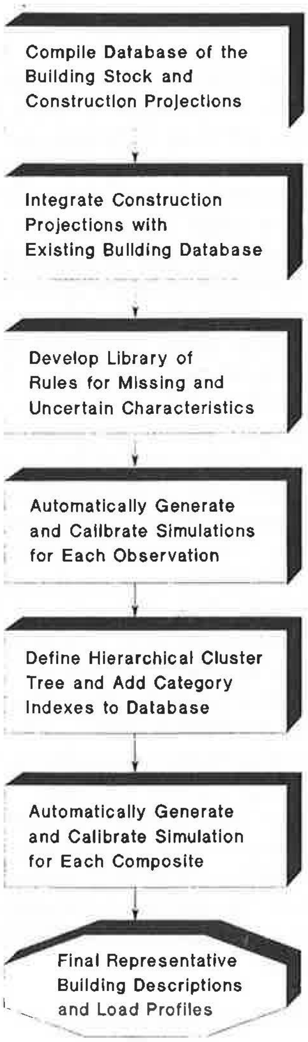

Figure 3 *Proposed approach for developing models of the building stock*

building retirement, it was possible to generate a set of building weights reflecting each building's expected representation in future years. Regional variations in growth projections and trends in building sizes and numbers of stories were imbedded in these adjusted building weights.

Trends in building construction—e.g., the penetration of new systems or declining use of others—were implemented as rules similar to the rules we developed for other missing data. For example, ASHRAE/IES Standard 90.1-1989 (ASHRAE 1989) contains provisions for more stringent minimum equipment efficiencies, which are scheduled for implementation in 1993. Future buildings were added to the office data base as an additional piece of work and not as part of the original data base. Ideally, these would have been fully integrated with the building sample at the outset, and the date of construction would have been treated similarly to other building characteristics in defining building categories.

Automating File Creation In the office building study, we used an automated procedure, which was driven by rules and survey data, for creating DOE-2 input files. Input files were created automatically by a computer program from a large table containing the desired input parameter values. Other researchers have used similar methods for creating simulation input files that can be used even when rather limited information is available about the building to be simulated (Carroll et al. 1989). We expect such methods, once enhanced and refined, to reduce the process of generating and extracting simulation data to that of a function call.

Automating Simulation Calibration If end-use consumption data became widely available, there would be no reason to use modeling as part of the process for defining categories, as we have done; end-use consumption could be used directly to group buildings based on energy performance. However, this is unlikely to happen any time soon. Consumption data would need to be available for a significant sample of the building stock. Billing data, the only empirical source of consumption data that is available in sufficient quantities, are disaggregated by energy sources but never by end-uses. End-use metering programs have mostly been initiated by electric and natural gas utilities, and there is currently no national data base containing these data.

In the office building study, bin-method simulations for each office building in the NBECS office building sample were calibrated to the NBECS billing data. This resulted in predicted energy consumption levels that matched NBECS consumption levels on average, but that explained only a small part of the variation in energy consumption seen in the billing data. Better results could have been obtained if each observation could have been individually calibrated to the billing data. This was computationally infeasible at the time but may not be so in the future.

Calibration of simulations to metered data is difficult for several reasons. There are a large number of degrees of freedom in a complex simulation model; many different combinations of parameter values can result in exact matches to aggregate annual consumption levels. Other constraints must be imposed if the values of calibrated parameters are to be meaningful. In addition, some conditions and events that significantly affect energy use are outside the capability of current energy simulations to model. Finally, though probably less important, there may be shortcomings in model algorithms and programming errors in simulation codes. All of these factors tend to make simulations difficult to calibrate and limit the reliability of calibrated simulations, serving to cloud the picture we are able to construct with them of how the building stock uses energy.

These problems not withstanding, a number of researchers have begun to address the problem of systematic calibration of first-principle models to empirical data (Carroll et al. 1989; Subbarao 1989). The problem of excessive degrees of freedom has most frequently been dealt with by employing simplified models having fewer degrees of freedom. Other researchers have worked with iterative, rule-based systems for calibration. An alternative approach, which we have been exploring, is to calibrate simulations to

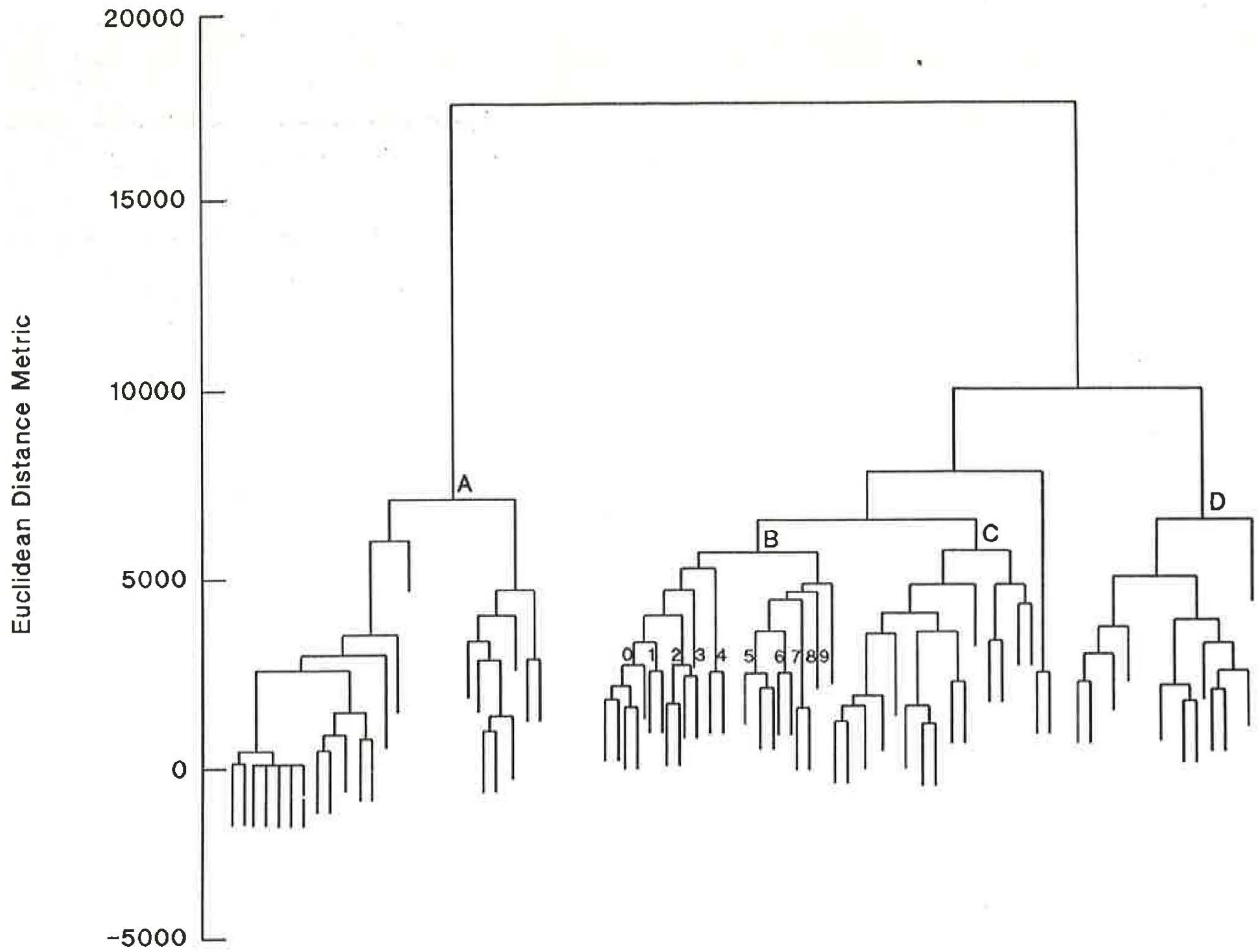

Figure 4 *Example cluster tree showing relationships between observations in a data set and the groupings formed in clustering them. The Euclidean distance between clusters can be read from the vertical axis at the height of their merger.*

empirical energy-use data within constraints based on a priori knowledge. This approach works by defining a maximum-likelihood objective function and solving for the parameter set that provides the best match, given both the theoretical and empirical information sources. Although it is unclear how successful these efforts may ultimately be, we believe they hold significant promise for improving our ability to understand and model building energy use.

Defining Hierarchical Clusters The procedure that we used to categorize the office building sector belongs to a class of cluster-analysis procedures described as hierarchical. In hierarchical procedures, clusters at one level are combined to form larger clusters at higher levels, ultimately leading to a single group containing all buildings in the sample. Figure 4 shows a tree diagram from a cluster analysis reflecting the nature of the hierarchical clustering process. The hierarchy of clusters growing out of these procedures has a potential application to the study of building populations.

In the office building study, we created a fixed number of representative buildings for use in studying the nation's existing office building stock. In our case, the number was somewhat arbitrarily set at 20, representing what we felt provided a reasonable trade-off between ease of use, time in development, and analytical power and resolution. Deciding how many clusters to select is a necessary step in using clustering procedures. In the case of the office building study, the number of clusters, categories, and representative buildings could have ranged from 1 (a single office building representing the entire stock) to 1139 (one for each office building in the 1979 NBECS).

Given that automated file creation is an essential feature of the approach that we envision, it would be only incrementally more difficult to create a hierarchy of representative building descriptions than to create a fixed set. Researchers could choose from among several levels of representative buildings depending on the resources available for the study and the research questions. For example, a researcher examining the suitability and in-building performance of new-technology HVAC equipment might first assess its performance using a set of four representative office buildings covering most of the office building stock (labeled A, B, C, and D in Figure 4). After confirming high suitability of one of the four buildings (e.g., B), analysis might be continued using 10 or so building descriptions found at a lower level of aggregation in the same branch of the tree structure (designated in Figure 4 with numbers 0 through 9). With each lower level, greater resolution would be realized, since the representative buildings would reflect more of the actual diversity in the building stock, although more analysis would be involved. This process could be continued down to the level consisting of all buildings in the original sample. Rather than each building observation in the data base being keyed to a single representative building description, as in the office building study, each observation would be keyed to a family of representative buildings, each of which could readily be generated from the data base and sets of rules.

Automatic Generation and Calibration of Simulations The remaining steps leading to the final representative buildings involve simple reapplication of capabilities defined earlier in the process. Using a file creation system capable of generating building simulations from rules and tables of values, a single set of simulations or a complex hierarchical set could be readily generated. Large sets of simulation input files could either be distributed ready for use or regenerated by the user. Calibration of the representative buildings would be a minor task, since the building descriptions would be composites developed from building descriptions that had already been calibrated to billing data.

APPLICATIONS AND IMPLICATIONS OF A FULLY DEVELOPED METHOD

Many of us started doing hourly simulations on mainframe, time-shared computers where an annual simulation of a large building might cost several hundred dollars. Today, these same analyses are more often done on personal computers or workstations, and computer time charges are usually not a consideration. We see a range of different types of worthwhile analyses that can be performed using this emerging computing power in combination with the sorts of capabilities discussed in this paper. Brief descriptions of some of these types of analyses follow.

Sensitivity Studies

One of the best strategies for decision-making in the face of uncertainty is to conduct sensitivity studies. Study conclusions are strengthened by the discovery that uncertain assumptions are not important, and they can be qualified when it is discovered that they do matter. The automated file generation capabilities described in this paper make extensive sensitivity studies very easy to perform. Inherent in the data base approach to building studies is information about the distribution of many characteristics within each category. This information can provide a concrete basis for defining reasonable parameter ranges for some types of sensitivity studies.

Other Large-Scale Studies

Automated generation of input files and the automated compilation of simulation results make it possible to use the results of simulation in new ways. Ten years ago, a typical building energy study probably would have involved only a few parametric runs designed to assess the performance of several major systems or options. Today it is possible to readily generate large numbers of simulation results using automated procedures for managing input and output. Simulation results can themselves be modeled using statistical methods. The ASHRAE/IES Standard 90.1-1989 (ASHRAE 1989) envelope procedure, in which regression analysis was used to model building loads, is a good example of this kind of application.

Optimization

Another promising application of this evolving capability is its application to optimization. This capability is a component of the whole-building targets methodology now under development by ASHRAE SP 52. Other researchers have used regression analysis of DOE-2 output to derive simplified expressions relating fenestration performance to design parameters and are using these expressions with optimization algorithms (Sullivan and Selkowitz 1989). Since such relationships can be characterized effectively using low-order polynomial expressions, they are easily incorporated as parts of objective functions for use in economic and performance optimization.

This type of optimization capability may ultimately be applied to the problem of strategic planning of building energy research. Using a set of representative buildings with known ties to a projected building stock, researchers could describe a set of future building technologies. Wherever those technologies were selected as part of the economically optimal set would constitute an area of suitability (or potential market niche). By varying parameters and assumptions, the potential energy impact and first-cost and energy-cost sensitivities could be objectively established. This process could also be used in assessing competition from other emerging technologies that a new system may face when eventually brought to market.

Application to End-Use Metering Studies

Several electric and natural gas utilities have initiated building end-use metering programs to accurately determine the end-use composition of utility loads in the commercial sector. The ultimate use of this information is for assessing and planning programs to manage the intensity and timing of demands on utility systems. Many of the procedures that we have described appear well suited for use in addressing these analysis needs.

As with our office building characterization study, end-use metering projects that we envision would begin with a survey of utility customers. This could be a survey of all buildings or a statistical sample of them. The more building characteristic information gathered in this survey, the more information would be available for informing end-use management policy. Using a rule-based approach for modeling the surveyed buildings, buildings could be modeled and calibrated to billing data. Cluster analyses would then be performed on the surveyed buildings, assigning them to categories based on energy-related parameters. Using the multidimensional distance metric calculated as part of the cluster analysis, the buildings within each cluster could be ordered based on their distance from the center (or weighted mean) of the cluster. This ranking would serve as an ideal candidate list for buildings to undergo detailed end-use metering.

Buildings selected for end-use metering would undergo a more detailed survey than performed in the initial survey of utility customers. New data would replace estimated parameter values assumed during the initial modeling effort. Once short-time-interval, end-use metered data became available, these data would be applied to calibrating simulation models for the metered buildings. It would be desirable in this modeling calibration process to drive the simulation models using actual metered data, such as lighting and receptacle loads, and to use actual data streams from local meteorological sites. Calibration of simulations using short-time-step (e.g., hourly) data is obviously more difficult than using annual or monthly values; however, some promising efforts have already been made in this direction.

As in our office building study, the approach we have described would link demographic building information with the capability to perform detailed analyses. Each metered building would have an explicit relationship to a segment of buildings in the service area. This explicit linkage would help utilities to interpret assessments of load management strategies conducted using the calibrated simulations by providing a reliable information base from which to generalize results.

SUMMARY AND CONCLUSIONS

- To conduct technology assessments and strategic planning of building energy research, it is necessary to bring accurate information about the size and composition of the building stock together with the capability to conduct sophisticated engineering analyses. This linkage is essential for informed decision-making.
- The increasing availability of good-quality end-use metered data provides opportunities for improving the reliability and accuracy of models of end-use loads. Integration of empirical data with predictive models is difficult to achieve, yet it will be an important aspect of future efforts to better understand energy issues in the building stock.
- The field of building energy analysis is evolving from reliance on case studies and subjectively defined building categories toward reliance on more sophisticated analytical techniques. This evolution is made possible by improving data sources and computational capabilities, and appears likely to continue. We expect it to substantially improve the capabilities to plan and assess research and development related to commercial building energy use.
- Building energy simulations are becoming much easier to productively exploit as automated methods are developed for input file development, execution, and interpretation. Several of the techniques developed in this work lead us to believe that there are new and powerful applications for simulation models that remain to be explored.

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