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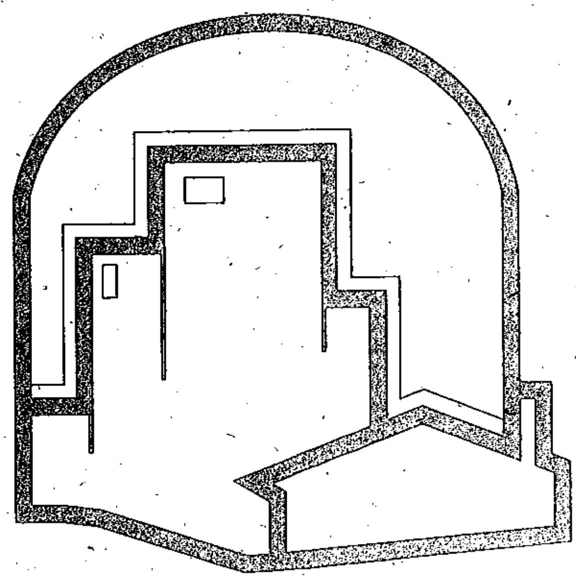

ACEEE 1990 Summer Study on Energy Efficiency in Buildings

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Performance Measurement and Analysis

American Council for an Energy-Efficient Economy ACE³

AN INVESTIGATION OF THE USE OF PROTOTYPES FOR COMMERCIAL SECTOR EUI ANALYSIS

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Prototypes are commonly used in forecasting commercial sector energy demand by end use. The basic idea is to create a description of a prototypical building that is broadly representative of a whole class of buildings. The description is often in the form of an input to a building energy simulation program for two reasons. First, the results of the simulation can form the basis for estimates of space conditioning energy utilization intensities (EUIs). Second, the performance of technology options can be modeled explicitly through selective modification of the simulation inputs.

The methodological question that arises in developing prototypes is how best to aggregate and "average" features of many distinct buildings into those of a single, prototypical building. This paper reports our investigation of two procedures for aggregating the characteristics of individual buildings into those for a prototypical building.

We used both floor area and an exogenously provided variable as weighting factors to develop two separate prototypes from the same set of individual buildings. Hourly energy use simulations were then performed both for the individual buildings and for the two prototypical buildings. The results of the individual building simulations were then aggregated to a single number using each of the two weighting schemes and compared to the results from simulating the prototypes. The procedure was applied to a sample of seven small (<30,000 ft^2) office buildings located in Southern California.

We found reasonable agreement between the weighted average simulation of individual buildings and those of the prototype for space cooling and fan energy use. Large percentage differences for space heating were deemed of secondary importance due the relatively small heating loads found in the buildings. Our findings led us to comment on some of the difficulties inherent in applying linear averaging procedures to non-linear thermodynamic processes and their significance for the use of prototypes in forecasting and demand-side planning.

INTRODUCTION

The basic energy unit of analysis for commercial sector end-use demand forecasting is the "energy utilization intensity" (EUI) expressed as energy use per unit area (kWh/ft^2). A separate EUI is developed for each end use (e.g., lighting, cooling, heating) and distinct sets of end-use EUIs are developed for each building type (offices, retail, food). There are many approaches for estimating EUIs ranging from end-use metering of individual buildings to statistical correlation of building characteristics (taken from surveys of many buildings) to measured total energy use. One of the earliest and still potentially most attractive approaches relies on the use of prototypical buildings. The basic idea is to create a description of a single building that is representative of the energy using characteristics of a whole class of buildings. The description is generally in the form of an input to a building energy simulation program. Often there are two objectives. First, the results of the simulation can be used directly as space conditioning EUIs and load shapes. Second, the performance of technology options can be modeled explicitly through selective modification of the simulation inputs. This latter capability is very desirable for those interested in using prototypes to evaluate the impact of demand-side management options.

The methodological issue that arises when developing prototypes is how best to aggregate and somehow "average" the features of many distinct buildings into those needed to describe a single, prototypical building. In this paper, we report results from an evaluation of one such averaging technique, which we examine using two different sets of weights. The evaluation was performed as part of a larger project to develop commercial sector end-use EUIs and load shapes for energy demand forecasting (Akbari et al. 1989). An important, intermediate step in the project was the development of building prototypes for simulation with a building energy analysis model. The prototypes were developed using a customized software package that aggregated and averaged detailed building characteristics data collected by field surveys of commercial buildings in the Southern California Edison Company (SCE) service territory.

The objective of this paper is to describe a method for creating and evaluating the energy performance of prototypical buildings. The paper is organized in five sections following this introduction. In the next section, we provide background on the subject of prototype development, describe the data available for our evaluation, and outline the methods developed to create prototypical building descriptions from those of individual buildings. We then describe the evaluation procedure used to test the prototypes. Next, we present our findings for the building type examined and discuss their significance. The final section contains our conclusions.

PROTOTYPE DEVELOPMENT

Historically, prototype development has relied primarily on "engineering judgment." This approach is inevitable given the large amounts of data required to specify a building completely for a simulation program and the difficulty (and expense) of obtaining significant quantities of these data from actual buildings. Typically, the most detailed information available from large samples of buildings is that collected by mail surveys. Yet, mail surveys are useful for specifying only a handful of important building characteristics (such as, floor area, number of stories, predominant lighting fixture types, heating and cooling fuels); detailed information on building construction and operation is generally not available (moreover, it is doubtful whether a mail survey could ever be expected to collect this information reliably). Consequently, the analyst must rely on familiarity with commercial building practices to supplement the limited information available from mail surveys. This practice often results in the development of "representative" buildings (i.e., a building description largely based on an actual building, but "modified" (often, in an undocumented manner) to be more reflective of a larger population of buildings).

In the absence of measured data from large numbers of buildings to validate these approaches, it is difficult to judge the accuracy of using prototypes to estimate commercial sector end-use EUIs. There are two distinct validation issues: First, how well does the aggregation of individual building characteristics into those of a single prototype capture the aggregate energy use of the individual buildings. Second, how well does the aggregation capture energy use of the population of these building types in the sector, given that the individual buildings represent only a sample of the total population. We will directly address only the first of these questions in our analysis, although we will evaluate a procedure that begins to (but does not completely) address the latter. (We will also not address an important third issue: how well do modifications to a prototype to model, say, the introduction of a new demand-side management technology reflect the aggregate performance of that technology in the field.)

Our analysis is based on a unique set of building characteristics data collected by trained building auditors who completed an extensive 32-page audit form for nearly 400 commercial premises (ADM Associates 1986). The data are unique both because of the level of detailed information collected and because of the large numbers of buildings surveyed. The data collected are far more comprehensive and detailed than information collected by mail surveys. With a few exceptions, the data were sufficient to support development of a complete building energy simulation input for each building with a minimum of "engineering judgment." Of course, some amount of judgment is unavoidable and necessary; we will comment on this issue later.

We developed an automated procedure for using the surveys to create a building simulation input for either a prototypical or an individual building. For prototype development, the procedure reads data from a predetermined number of individual audits (set by the number of audits available for a given building type), and averages these data using an exogenously specified weighting factor. For example, the floor area of the prototype is the weighted average of the floor areas of the buildings multiplied by their respective weighting factors. The calculation is repeated using the same weighting factor for each physical component and operational aspect of the building. The output of the procedure is an input to the DOE-2 program (BESG 1984), which is then used to simulate the energy performance of the building. A detailed discussion of the overall prototype development process is contained in Akbari et al. (1989). The basic algorithms used to define the physical characteristics of the prototype are contained in ADM Associates (1983).

For estimating prototypical non-space conditioning energy use (e.g., lighting and miscellaneous equipment), the application of this procedure is uninteresting because the estimation of energy use for these processes is linear (e.g., intensity times hours of operation). Consequently, linear combinations of these calculations for the purposes of prototype development are just arithmetic exercises. Non-space conditioning energy use is, however, important for consistent treatment of the impacts of non-space conditioning energy use on space conditioning energy use (i.e., the effects of internal gains on heating and cooling loads). Although there is a significant question as to the accuracy of the surveyed data used to make these calculations, the calculations themselves are of secondary interest and will not be reported on in this paper.

The more interesting question regards the use of prototypes to estimate space conditioning energy use (cooling, ventilation, and heating). The interest stems from the assumption of linearity built into any averaging scheme and the contradiction to this assumption that characterizes actual building energy use. A striking example of this contradiction arises when considering building operating schedules. Despite a distribution of starting and stopping times for a ventilation system, a single choice of start and stop time must be made for a prototypical ventilation system. This choice assumes that the energy use of systems, which start at later times, is exactly balanced by the energy use of systems, which start at earlier times. Additional difficulties with the use of prototypes include the need to specify a single HVAC system to reflect the aggregate behavior of many different types of HVAC systems and the need to select a single orientation for the prototype, among others.

In essence, our investigation of the use of prototypes is an evaluation of how well a particular averaging scheme can reflect the aggregate behavior of a set of inherently non-linear systems.

A METHOD FOR EVALUATING PROTOTYPES

To evaluate the procedures developed to create prototypical building descriptions, we devised a simple test. First, for each individual building in our sample, we created a building description and simulated it using DOE-2. These simulations are referred to as individual building simulations. Second, we created and simulated a prototypical building drawn from the characteristics of the individual buildings in the sample. The simulation of the prototypical building is referred to as the prototypical building simulation. Third, we weighted the results of the individual building simulations using the same weights used to develop the prototypical building. The comparison of the weighted individual building simulations to the prototypical building simulation forms the basis of our evaluation.

We examined two weighting schemes. The first used the floor area of the buildings as a weight. The prototype developed using this approach is called the floor area weighted prototype. The second used an exogenously determined "sample" weight designed to better reflect the representativeness of each individual building relative to the population of these buildings in the SCE service territory. The prototype developed using this approach is called the sample weighted prototype. Because, in the second case, we will not compare our results to the aggregate energy characteristics of the population of SCE buildings (which are not available, in any case), our examination of the sample weighted prototype is only a look at the effects introduced by the use of a particular weighting scheme relative to the individual building simulations.

The analysis was performed using a random sample of seven small offices ranging in floor area from 117 to 27,000 ft^2. The heating system was assumed to be gas fueled and the cooling system was assumed to be electrically driven for both the prototypes and the individual buildings. The simulations were performed using an hourly weather tape for the Los Angeles region.

ANALYSIS OF PROTOTYPES

Table 1 summarizes our results for space heating, cooling and ventilation. We note first the large spread of individual EUIs for space heating, from less than 1 to over 60 $kBtu/ft^2$. Closer analysis of these values reveals that there was little heating for most of the buildings so that the EUI consists largely of gas use by the pilot light, which was a fixed value that depends on the number of gas appliances (in this case, one per building), not their size. The EUI is simply this fixed value divided by the widely varying floor areas of the individual buildings. For example, use of the pilot light in the smallest building (#4, at 117 ft^2) produces an extremely large EUI.

Cooling EUIs ranged from almost 2 kWh/ft^2 to over 8 kWh/ft^2 (again, the large value was associated with the building with the smallest floor area). Ventilation EUIs exhibited the smallest range, from 1.6 to 3.1 kWh/ft^2. We observed that the ventilation EUI often exceeded the space cooling EUI. This should come as no surprise; cooling requirements in the relatively temperate climate of Los Angeles can often be met with an economizer cycle. Compression cooling is only required during the hottest season, yet mechanical ventilation operates year-round.

Referring again to Table 1, we found significant differences (>10%) between EUIs of the prototypes and those derived from the weighted sums of the individual buildings. For both prototypes, the space heating EUI was lower than the weighted sum of the individual buildings (by 20% and 12% for the floor area weighted and sample weighted prototypes, respectively) and the space cooling EUI was higher (by 8% and 26%, respectively). The ventilation EUI was lower for the floor area weighted prototype (by 11%) and higher for the sample weighted prototype (by 20%).

For space heating, the relative differences are not of significant because the absolute values are small. As noted above, gas is used primarily to keep the pilot light burning. The actual heating loads met by the gas heating systems are quite small. (Indeed, subtraction of pilot light gas use from the totals produces even greater percentage differences in gas use for heating.) However, despite large percentage differences between values, they should be considered roughly equivalent.

The differences for space cooling are of greater interest. The estimated EUIs are all significant in absolute size and those estimated for the prototypes are consistently high. The difference for the floor area weighted prototype comes closest to the weighted sum of the individual building simulations (8%). Some insight into the differences is gained by examining cooling energy on a monthly basis (see Table 2). We found that the floor area weighted prototype had somewhat higher cooling energy use in the late winter and early spring months (about 10% greater), but was in close agreement with the weighted sum of the individual buildings for the summer months. For the sample weighted prototype, we found close agreement in the winter months, but substantial overestimation in the summer months (in excess of 30%).

Table 1. Comparison of Space Conditioning EUIs

Building Identification	Floor Area (sq.ft.)	Statistical Weight	Space Heating EUI (kBtu/sq.ft.)	Space Cooling EUI (kWh/sq.ft.)	Ventilation EUI (kWh/sq.ft.)
#1	13,500	133.4	0.52	2.87	3.19
#2	7,086	133.4	1.22	1.86	1.61
#3	1,800	603.4	3.90	3.98	2.85
#4	117	8,781.4	63.50	8.75	3.03
#5	1,350	2,495.1	6.41	2.09	1.74
#6	1,000	2,495.1	10.06	1.97	1.94
#7	26,792	320.7	0.49	3.10	2.40
Floor area weighted sum of individual buildings	7378		1.20	2.86	2.49
Floor area weighted prototype	7378		0.95	3.10	2.22
Prototype as percentage of individual buildings			79%	108%	89%
Statistically weighted sum of individual buildings	1291		6.34	3.05	2.32
Statistically weighted prototype	1291		5.61	3.84	2.80
Prototype as a percentage of individual buildings			89%	126%	120%

Further comparison of the monthly energy use values against those of the individual buildings along with consideration of the effect of the weighting procedure is even more revealing. The monthly pattern of energy use for the floor area weighted prototype is very similar to that of building #7. For the sample weighted prototype the greatest similarity is found with building #3. This should come as no surprise: Depending on the weighting factors used and the actual distribution of individual buildings, the prototype will tend to "look" like whichever individual building happens to come closest to being the weighted central value of the distribution (although, there may not, in fact, be such a building in the distribution). In the case of floor area weighting, the bulk of the weight is carried by the largest building, which is #7. Accordingly, the prototype exhibits energy-using characteristics similar to that of building #7. In the case of the sample weighted prototype the relationship is less clear, but building #3 appears to beclose to the weighted central value for the individual buildings (as evidenced by its floor area being close to that of the prototype).

This observation also appear to underlie the results for fan energy use. Analysis of the monthly data reveals the differences to be a constant percentage throughout the year. Thus, the difference lie in the scheduled hours of operation and in the sizing of the fans. Close correspondence in monthly EUIs

Table 2. Analysis of Monthly Cooling EUIs

Individual Buildings Cooling Intensities Building	1	2	3	4	5	6	7
January	0.04	0.03	0.09	0.64	0.07	0.09	0.05
February	0.03	0.03	0.07	0.57	0.06	0.07	0.04
March	0.06	0.04	0.09	0.63	0.06	0.08	0.10
April	0.12	0.09	0.21	0.66	0.11	0.12	0.17
May	0.16	0.11	0.23	0.68	0.11	0.12	0.23
June	0.32	0.22	0.48	0.70	0.21	0.15	0.39
July	0.56	0.34	0.71	0.97	0.37	0.33	0.53
August	0.60	0.33	0.69	0.97	0.36	0.34	0.51
Sept.	0.48	0.32	0.67	0.87	0.33	0.28	0.51
October	0.33	0.23	0.48	0.79	0.23	0.20	0.38
November	0.09	0.07	0.14	0.62	0.09	0.10	0.12
December	0.07	0.05	0.13	0.64	0.09	0.10	0.08
Total	2.87	1.86	3.98	8.75	2.09	1.97	3.10

Comparison with Floor Area Weighted Prototype				
	Prototype	Weighted Sum of Ind.	Percent Diff.	Percent Diff. of Prototype from Bldg. #7
January	0.06	0.05	115	115
February	0.05	0.04	117	110
March	0.09	0.08	120	97
April	0.16	0.14	114	99
May	0.22	0.19	117	98
June	0.38	0.34	113	99
July	0.53	0.51	103	99
August	0.51	0.51	101	100
Sept.	0.50	0.47	106	98
October	0.37	0.34	109	99
November	0.13	0.10	122	106
December	0.09	0.08	116	100
Total	3.10	2.86	108	100

Table 2. (contd)

	Prototype	Weighted Sum of Ind.	Percent Diff.	Percent Diff. of Prototype from Bldg. #7
January	0.10	0.09	109	109
February	0.08	0.08	100	117
March	0.10	0.11	91	110
April	0.20	0.17	119	99
May	0.22	0.20	106	95
June	0.44	0.33	133	93
July	0.67	0.51	133	94
August	0.66	0.50	132	95
Sept.	0.63	0.47	135	94
October	0.46	0.34	133	96
November	0.15	0.13	109	101
December	0.14	0.12	119	102
Total	3.84	3.05	126	96

were observed between the floor area weighted prototype and building #7 and between the sample area weighted prototype and building #3.

THE SIGNIFICANCE OF THESE FINDINGS FOR THE USE OF PROTOTYPES

We have developed and tested an averaging method for creating a single prototypical building description from many individual building descriptions. Significant non-linear aspects of the effects of various features of building construction and operation on energy use were suppressed by the linear assumptions inherent in our averaging method. The accuracy of the averaging method (as measured by how close the energy use of the prototype came to the weighted average energy use of the individual buildings, was found to vary depending on end use and, more importantly, on the choice of weighting factor. Use of floor area as a weighting factor led to prototypes that more closely reflected the energy use of the weighted sum of the individual buildings than did the use of an exogenously specified, sample weighting factor.

If our interests were limited to determining which weighting factor led to the best agreement, recommending the use of floor area as a weighting factor would be the simple conclusion of our investigation.

However, our larger interest lies with the use of prototypes for commercial sector forecasting and, specifically, with the use of linear averaging methods to approximate the behavior of inherently non-linear energy systems. On these grounds, our findings should be somewhat disturbing. Given that the choice of weighting factors was more or less arbitrary for the purposes of our investigation (i.e., we really did not intend, at this point, to use the prototypes to draw conclusions for a population of buildings greater than those examined, which would be our objective if we were using the prototypes to forecast commercial sector energy use), it is very significant that we found the choice of one set of weighting factors to lead to a "better" prototype than did the other. The reason for our concern is that, in some sense, it was only accidental that the use of floor area as a weighting factor lead to development of a more accurate prototype. In other words, if the suppressed, non-linear effects of features of building construction and operation on energy use had been adequately approximated by the linear assumptions underlying our prototype development methods, the choice of weighting factor should not have been issue in the relative accuracy of the two prototypes; the percentage errors should have been more or less the same.

We must therefore conclude that it is not sufficient to ensure, as we have done in this study, that each individual physical and operating characteristic of a sample of buildings is carefully weighted and averaged in the creation of a prototype because the energy performance of the sample, much less a larger population, cannot be approximated by such a linear averaging of these characteristics. Instead, some other form of "averaging" must be performed.

While one could surely refine aspects of our prototype development method, this conclusion should be a sobering thought for those involved in the use of prototypes. It implies that explicit, independent validation of the energy performance of a prototype may be required before it can be reliably used for estimating the space conditioning energy use of a given stock of buildings. (This is to say nothing about the use of prototypes to estimate counterfactual situations involving the performance of specific demand-side measures.)

The dilemma is that some fine-tuning or calibration of the prototypes appears to be required, yet the empirical basis (the information on building characteristics and operation) for this fine-tuning has already been exhausted. In other words, the process of calibration will require the introduction of other information and "engineering judgment" that is not supported by the characteristics data available from the sample (in particular, about the most appropriate methods for representing the aggregate behavior of the non-linear aspects of building energy use).

For example, one approach might be to make use of the recorded energy use data from the individual buildings. Meaningful use of these data might be accomplished through calibration of the simulation inputs for the individual building. The irony is that, at this point, the value of aggregating the characteristics of individual buildings in order to create a single prototype might be a step backwards. That is, the problems inherent in prototype development stem, in some sense, from the heterogeneous (non-linear) energy using characteristics of even a small sample of commercial buildings. Approximating the distribution of these buildings with a single prototype might be unnecessary, if one now has calibrated simulation inputs for each observation in the distribution.

At this time, we cannot determine whether developing better individual building characteristic "averaging" procedures (in order to develop better prototypes) is a more cost-effective means for understanding commercial sector energy use than is developing better individual building modeling capabilities (and not bothering with the intermediate step of prototype development altogether). Our goal in this discussion has been only to suggest that the limitations we found in creating prototypes, which could only be revealed by the extensive data we had available for our analysis, make it a legitimate question to ask whether future commercial sector forecasting efforts should continue to rely on a single prototype for each building type.

CONCLUSION

We developed an automated procedure for linearly aggregating and averaging the characteristics of individual buildings into those for a single prototypical building. We tested the procedure by simulating the energy performance of each building in a sample and that of a prototype developed to represent the aggregate energy performance of these buildings using the DOE-2 building energy analysis program. The energy use of the prototype was then compared to that of the weighted average of the individual building simulations. The test was applied to a sample of detailed audit data for seven small offices. Two prototypes were developed each using a different weighting scheme to aggregate the characteristics of the individual buildings.

We found that our prototype development method could not consistently produce prototypes that were equally representative of the energy performance of the weighted sum of the energy performance of the individual buildings. We concluded that the linear assumptions embodied in our prototype development methods were an unreliable approximation of the aggregate impact of the non-linear effects of building construction and operational characteristics on space conditioning energy use.

These findings led us to suggest caution in the use of prototypes for energy demand forecasting and demand-side planning. While use of prototypes is probably unavoidable, we believe the need for validation and calibration is significant. We speculated that these needs might call into question the very basis for the use of prototypes in forecasting commercial sector energy use.

ACKNOWLEDGMENT

The work described in this paper was supported by the Southern California Edison Company and by a grant from California Energy Commission through the University of California Universitywide Energy Research Group's Program in California Energy Data Analysis. Preparation of this paper was in part supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Building and Community Systems, of the U.S. Department of Energy, under contract no. DE-AC03-76SF00098.

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