ENERGY CONSUMPTION BUILDING PERFORMANCE MODELS

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ABSTRACT

Investigation has shown that poor design and construction techniques in the building industry have produced many buildings which contribute greatly to the "energy crisis." These buildings waste energy and approximately 40% of this wasted energy is due to poor design. Energy is consumed in buildings in many different ways; however, modern computer techniques allow the development of easily used pre-construction energy consumption building simulation models. The theory utilized in these models is explained and three existing models are discussed in this paper. The three models presented demonstrate the three sectors currently investigating energy consumption: commercial, educational and governmental. While energy consumption prediction techniques are currently available, these must be used by architects and engineers to be effective. In addition, more research is necessary to ensure that prediction techniques are utilized to their maximum benefit. Suggested areas of future investigation are material properties, man-environment interaction with energy saving measures and conservation devices for existing construction.

INTRODUCTION

The recent disclosures concerning the current "energy crisis" have made all sectors of society acutely aware of resource scarcities. These scarcities are particularly evident in the area of energy commodities and are reflected in the spiraling costs of fuels and other energy sources. Scientists, economists, engineers and others have published reports predicting the complete depletion of the world's energy resources in times ranging from sixty to 150 years. In Limits to Growth (Meadows, et al, 1972) it is demonstrated very well that resources of all types are being consumed at an increasingly alarming rate, and, if more care is not exhibited in the rationing of these resources, the world will suffer a severe setback within the next one hundred years. Variations in time are only dependent upon the analysis method employed by a particular writer. However, the difference in time is actually not the main concern. The development of methods to revise the trends of energy consumption in the world and in all areas of use is of the utmost importance.

Energy related research is currently assuming many forms. One of these forms is the development of new energy sources which is being studied by a number of researchers. However, to allow time for new energy sources to be developed, the current energy consumption rate must be reduced. Some energy conservation programs are currently underway in this country on a national basis. Last Christmas outdoor decorative lighting was greatly reduced by request of the President of the United States. In addition, many heating thermostats were set back to 68° during the winter months resulting in large savings of available fuel. By Act of Congress highway speed limits have been reduced to 55 miles per hour on the nation's highways and many national, state and local governing officials have been given broad emergency powers to act as they feel necessary to save energy. However, little study has been directed toward energy conservation measures as a guide to the design or construction of buildings. The setting back of thermostats controlled heat within the building, but did not consider the differential energy necessary to maintain that heat in different buildings.

According to a recent report of the Stanford Research Institute, heating and cooling alone for residential and commercial buildings in the United States accounted for approximately 20% of the total energy consumed in this country. Of the energy used in buildings, studies have shown that about 40% is wasted due to poor design (Caudill, et al, 1974). If buildings are properly designed, this wasted energy can be saved and would result in the saving of approximately 65 billion buckets of oil a year. It is therefore extremely important that conservation of energy is addressed as a criterion for building design.

ENERGY CONSUMPTION IN BUILDINGS

During the past two decades the construction industry has enjoyed rapid technological growth. Development of new materials and improvement of old materials have produced more efficient structural systems allowing heavier loads to be carried by elements composed of much less material. Curtain walls have produced faster construction and thinner building exteriors. Production of glass in large sizes has allowed great expanses of glass walls exposed to the weather on all sides of a building. Developments in interior lighting have proliferated lighting fixtures and have added greatly to the consumption of electrical power. All of these and similar advances have produced attractive buildings, but many of these "improvements" have also greatly increased energy consumption in buildings. Environmental problems produced by large expanses of glass exposed to the sun were solved by the simple installation of a larger air conditioning unit. Consequently, building orientation, in many instances, became less important than standardized plans or architectural visual effects.

Commercial architecture is not alone to blame. Residential consumption of power has been increasing at an ever accelerating rate. A more affluent populace demanded more and better housing. The move to the suburbs was accompanied by a single family residential boom across the country. Unfortunately, energy conservation was not utilized as a design criterion in most of these residential units.

Before any construction can be commenced in many locations, approval must be obtained from the local government and a building permit must be issued to the builder. Such approval is normally granted after the architectural drawings are reviewed to ensure their compliance with local ordinances and construction codes. This review is normally conducted by the office staff of the local building inspector, and rarely is predicted energy consumption a factor in these discussions. However, with the current energy conscience as it is, predicted energy consumption most surely will be considered in the future. Because of this, methodologies available for predicting and evaluating energy consumption in buildings are presented in this paper.

PREDICTING ENERGY CONSUMPTION

Methods currently available to predict energy consumption in buildings vary widely in their approach to the problem and in their complexity. However, all methods include the same basic steps. First, each area of the building in question must be checked for construction and use to determine the predicted heat gain or loss. Secondly, the heat gain or loss must be utilized to compute the necessary load to be produced by the heating or cooling system. And, finally, the energy requirements of the heating or cooling system necessary to meet heating or cooling load must be determined. Each of these steps may be accomplished in any degree of accuracy or approximation desired by the engineer. However, the more complex the analysis method used, the more difficult and time consuming are the necessary computations. Consequently, the use of a high speed digital computer is mandatory when an accurate and complete analysis is desired.

In an effort to assist architects, engineers, and those other persons charged with the responsibility to evaluate building designs, a number of energy-related computer programs have been developed. From the commercial energy suppliers two major energy analysis and design programs have been prepared for commercial use. The Electric Energy Association has developed a computer program called AXCESS to assist architects and engineers to determine the electrical needs of a proposed building. The program is currently being revised to provide greater flexibility of analysis and more complete service to the user.

The second commercial program was developed by the American Gas Association and is called "ECUBE." This program is designed to assist designers in the decision process concerning energy conservation. It can be applied to proposed projects to evaluate space planning and material choices as they apply to energy and can also be utilized to evaluate proposed conservation measures on existing buildings. The ECUBE package consists of a group individual energy analysis program integrated to measure the effects of climatic conditions, building orientation, mechanical equipment, proposed space utilization and construction materials. The total package can be utilized to determine the energy requirements of a building, provide alternative choice of equipment sufficient to meet the predicted energy requirements, and evaluate the economic implications of these choices.

The program is available on a commercial basis and additional information can be obtained from the parent organization.

Many universities and other research organizations are investigating simulation models as a guide to energy consumption in buildings. One such model is currently being implemented and modified at the University of Kansas. The simulation model "ENCOM" is designed to compute the predicted energy consumption in a given building over a period of time. The approach is based upon the ASHRAE Handbook of Fundamentals which contains the basic information with which to calculate the heating and cooling load of a building. The model is mathematical in nature and lends itself to standard computational techniques. In its present form it can easily be adapted for different construction or design configurations. In addition to the predicted energy consumption for a building, ENCOM computes the predicted costs of that energy over the life of the building. The initial cost of the energy producing system, the operating costs, maintenance costs, and replacement costs are computed on a yearly basis in terms of their present worth. In this manner the "total cost" of the energy requirements of a building over its lifetime may be computed. The user then has the possibility of comparing a given set of economic factors for a particular design or material configuration with the predicted costs of a different design decision. These trade-offs can be investigated for both proposed or existing buildings being considered for construction, remodelling or renovation. Such analysis will allow the architect to investigate the balance between energy consumption, design and building costs. A proper balance will maintain the design integrity of the architect and produce a pleasing building at a reasonable cost which is within allowable limits for predicted energy consumption.

Initial investigations in this project have been directed toward residential construction. However, the techniques utilized would equally apply to any classification of building. Input data for the model is designed to describe the building, the building components, the climatic conditions and other known operating factors. Such input data is obtained from the architectural drawings, manufacturer's literature, operation cost records and other sources and consists of the following:

Building Description:

- a. Number of building subsystems
- b. Estimated life of the building
- c. Building configuration
    1. Number of rooms
    2. Individual room dimensions
    3. Exterior glass areas (each elevation)
    4. Building orientation
    5. Percent of shaded glass
- d. Building construction
    1. Foundation construction
    2. Floor construction

3. Roof construction
4. Wall construction
5. Window type, material, orientation
6. Door type, material, orientation

Climatic Conditions:

a. Number of cooling degree days per year
b. Number of heating degree days per year
c. Summer outside design temperature
d. Winter outside design temperature

Heat Gain or Loss Condition:

a. Normal population of the building
b. Burning hours per year of normal lighting
c. Average number of lighting watts per sq. ft.
d. People sensible heat gain factor
e. People latent heat gain factor
f. Average C.F.M.'s per person

Cost Computation Conditions:

a. Method of calculating annual depreciation
b. Kilowatt hour cost
c. Heating fuel cost per million B.T.U. output
d. Cooling energy cost per kilowatt hour
e. Average power input per cooling unit
f. Cooling capacity of cooling unit (B.T.U.)
g. Enthalpy value
h. Heating fuel percent increase per year
i. Cooling energy percent increase per year
j. Lighting energy percent increase per year

While this input data list appears to be quite long, the model is designed to receive the input necessary only to describe a particular combination of materials and design configuration for a given building. More permanent information is included as part of the main model and only needs to be changed when the situation demands a change. For example, the present model utilized was developed at the University of Kansas, so climatic data was assumed for the Lawrence, Kansas area. Analysis of a building to be located in some other geographic region would necessitate only the changing of a few lines of the program. This technique eliminates the need of including some information as input for all analyses in a particular location.

The analysis techniques utilized for the ENCOM consist of the computation of the energy consumption of each section or "subsystem" of the building and summing their values to obtain the total energy use for the complete structure. These figures are computed for the first year of the use of the building and then projected into the future by "factors" of expected change. The "factors" are based upon the relative scarcity of materials, efficiency of the subsystems over time, inflation of the economy and other predicted effects.

The actual mathematical computations are relatively simple in nature. For example, heating costs are determined by first finding the amount of heat lost through the exterior building surfaces and the amount of fresh air required in the building. By knowing the thermo-transmittance factor, U, for given exterior building subsystems such as floors, walls, glass and roof, and by knowing the physical dimensions of these surfaces, the heat loss can be calculated by the following formula:

$$\text{Heat loss} = Q = U \times A \times \Delta t$$

where:

U = Thermo-transmittance factor
A = Area of exterior surface
Δt = Temperature difference between inside and outside environments.

Once this value has been calculated for every exterior subsystem, a summation of heat loss for the total building is made. The quantity of fresh air required by the facility is calculated by the formula:

$$\text{Fresh air} = F = C \times P \times 1.08 \times \Delta t$$

where:

C = Number of CFM's per person/hour required
P = Average number of people using the space at a given time
1.08 = Fresh air constant
Δt = Temperature difference

Both the exterior surface heat loss and the fresh air requirements are in units of BTU's/hour. These two figures are then combined and yearly heating costs are computed as:

$$\text{Heating cost} = C_h = \frac{24 \times C \times Q^1}{1{,}000{,}000} \times \frac{D_h}{\Delta t}$$

where:

Q^1 = Heat loss + fresh air required (BTU/hour)
C = Cost per million BTU output ($)
D_h = Number of heating degree days per year
Δt = Temperature difference

This then becomes the heating cost for year 1 in the model and the heat energy (BTU) required is also available. Subsystem efficiency, cost increase and other predictive "factors" are then multiplied by these values to establish the predicted heat energy use or future heating costs for the particular subsystem or area.

Cooling costs are established much in the same manner as are heating costs. Cooling loads in a building come from both sensible and latent heat gain. The sensible gain (increase in air temperature) is built up by general heat flow. The latent load is the heat that must be withdrawn in order to condense the moisture and maintain a reasonable relative humidity. A building with large spaces, such as auditoriums, would present a greater latent heat problem than a residence because of its moisture-producing crowd and because the fresh air needed for ventilation also carries moisture. Sensible heat gain derives from solar transmission, exterior surface heat gain, people, and lighting. Latent heat gain derives from the number of people within the building and the C.F.M. fresh air required. All of these are taken into account in the model by a series of equations.

Transmitted and absorbed solar heat gain varies from a minimum of 7 BTU/hour/sq. ft. for north or shaded heat-absorbing double glass to 11 times this value (77 BTU/hr/sq. ft.) for east and west, single, unshaded glass. To obtain the solar gain, the model first calculates the average of the 5 hours of the day in which the sun affects the particular orientation to the greatest extent. It does this for each of the north, south, east, and west elevations and only for the most severe month of the year. These figures establish the average maximum BTU/sq. ft. solar gain for the building. Climatic charts are normally available to obtain this information for the particular latitude in which the building is located. The particular model discussed here assumes a 40 degree north latitude. The areas of glass on each elevation are then multiplied by these values and are established as the heat gain (BTU's/hour) for the building. Venetian blinds, roller shades, colored and reflective glass, and trees all provide shading of areas of the building from the sun. Thus, these shading devices must be taken into account in order to arrive at a final figure for solar heat gain. A "percent of non-shaded glass" is input into the ENCOM model to consider the effect of shaded subsystems. The heat gain established before is then multiplied by this percentage to arrive at the final effect of solar energy.

Heat gain through exterior building surfaces is calculated in exactly the same manner as was discussed for the heat loss computations. The only difference is the value of the "Δt", the temperature difference between the inside and the outside summer temperatures.

"People sensible" (heat from people) is calculated by multiplying the average population of the building by the BTU/person factor for the type of activities that occur within the building. In much the same way, heat from lighting is calculated by multiplying the number of watts of lighting in the building by 3.4 (the number of BTU's produced per watt). The solar gain, exterior surface heat gain, people sensible, and lighting heat gain are then totaled. The CFM's of air required is calculated by the formula:

$$\text{CFM} = \frac{\text{total sensible (BTU/hour)}}{1.08 \times \Delta t}$$

where:

Δt = Temperature difference between the summer inside and outside

Latent heat gain, the moisture given off by people, is calculated as follows:

People latent = (number of people) x (BTU's/person)

The BTU's/person again refers to the activities that the people within the building are performing. The use of this calculation will be discussed later.

In order to proceed with the explanation of cooling, it must be mentioned that because air, moisture, and heat are all related to each other, a mathematical relationship must be established. An air-conditioning engineer uses a diagram of these relationships called the "Psychrometic Chart" to determine various data needed for his calculations. The details of these charts need not be discussed here; however one item needed for the model's calculations is the "enthalpy value." This is the total heat in an air mixture above zero degrees Fahrenheit and including the latent heat of the water vapor. If this value is not specified the model assumes 9.4. This figure would be obtained from a psychrometric chart if the following conditions existed:

outside air	100^0 D.B.,	76^0 W.B.
inside air	78^0 D.B.,	66^0 W.B.
air entering coil	78^0 D.B.,	66^0 W.B.
air leaving coil	56^0 D.B.,	55^0 W.B.

where:

D.B. = Dry bulb temperature (air-water vapor mixture temperature measured on normal Fahrenheit thermometer)

W.B. = Wet bulb temperature (the temperature shown by a thermometer with a wetted bulb rotated rapidly in the air to cause evaporation of its moisture.)

The CFM's, the air moisture content required, and the sensible heat gain are all then related by the following:

$$E = \text{BTU/hour} = 4.5 \times (\text{enthalpy value}) \times (\text{CFM})$$

This value is then added to the latent heat gain to arrive at a final total "Q", for cooling calculations:

$$Q = S(\text{total sensible heat gain}) + L(\text{total latent heat gain})$$

After all of the previous steps have been completed and the cooling load established, a prediction can then be made about the cooling costs for the first year of operation. The following formula established this cost:

$$\text{Annual fuel cost} = C_c = \frac{24 \times c \times Q \times P}{Qe} \times \frac{D_c}{\Delta t}$$

where:

D_c = Normal cooling degree days
c = Cost per kilowatt hour of operation
Q = Cooling load (BTU/hour) under design inside and outside temperature
P = Average power input (kilowatts)
Q_e = Total cooling capacity of unit or subsystem (BTU/hour)
Δt = Difference between inside and summer outside temp.

A "factor" for cooling costs is then multiplied times this cost to establish its yearly increase or decrease.

Lighting loads comprise the third major component of energy use. The model incorporates this by the following equation:

$$\text{Annual lighting energy} = C_l = \frac{(\text{total watts}) \times (\text{burning hrs/yr})}{1000}$$

where:

Total watts = the total lighting watts throughout the building

The cost of lighting energy can easily be obtained by the multiplication of the annual lighting energy value by the established cost per kilowatt hour of operation.

While the ENCOM model utilizes a relatively simple approach to the computation of energy consumption and its associated costs, it is of sufficient accuracy to provide a useful research tool. However, if greater accuracy is desired and a more sophisticated approach is demanded, a useful series of computer models has been developed by the National Bureau of Standards utilizing the transfer function concept first introduced by Mitalos and Stephenson in 1967. The transfer functions are represented by what the authors describe as room thermal response factors and enable the simulation model to consider exterior temperature variations and space use variation during the analysis period. This concept provides a much more accurate result than the "design condition" approach utilized by the ENCOM model. The Bureau of Standards model, called NBSLD, is fully discussed in a publication to be distributed later this year (Kusuda, 1974) and will be available for university research programs.

UTILIZATION OF SIMULATION MODELS

The development of energy consumption simulation models remains an academic exercise unless corresponding uses of these programs are also produced. While energy consumption considerations have in the past been the responsibility of the "mechanical consultants", all personnel associated with the building industry are going to be required to become more energy conscious in the future. As this awareness of the problem increases, applications of energy oriented simulation models will also be developed. Some areas of necessary applications research will be discussed in this section.

One area where the application of energy consumption simulation models has obvious use is in the design evaluation phase of proposed buildings. Utilization of a computational model such as discussed in the preceding sections allows the pre-construction determination of the predicted energy consumption performance of a proposed building. If such an analysis were required by law, comparison of this information could then be made to maximum energy consumption levels determined for various classifications of buildings. Such an input could be utilized by local governmental agencies in a manner similar to other requirements of the local building codes. Utilization of these criteria would allow the architects and the contractors to develop and construct new buildings within a given locale in such a manner as to provide the maximum conservation of energy during the life of the building. Such a law is being considered in California at the time this paper is being written and may provide the model for similar laws in other sections of the country.

However, in order for such laws to become effective, much research must be conducted in a number of areas. For example, maximum allowable energy consumption levels must be determined for various classifications of buildings. In addition, building subsystems constructed of different materials must be investigated in an effort to provide architects and engineers with design data that will allow them to make decisions with energy conservation as a consideration. The efficiency of individual materials and combinations of materials must be investigated as must the inclusion of materials and equipment in various design configurations.

A particular area of concern for man-environment researches will be the interface between energy conservation measures in buildings and human productivity. As steps are taken to improve energy consumption within a building, adverse affects upon the human performance of people working within that particular space may result. A simple example of this would be if the window areas were reduced in an effort to reduce the heat loss through the glass. This could, in effect, produce spaces approaching a closed box. Such a space may be extremely unconducive to human productivity. As people react to both physical surroundings and the psychological effects of those surroundings, both aspects should be considered.

The evaluation of existing buildings is a necessary step in many areas. As explained earlier in this paper, existing buildings are wasting tremendous amounts of available energy. This high energy consumption rate can be reduced considerably with proper evaluation and application of corrective measures. For example, an analysis of a "typical" Colorado school authorized by the Colorado Commissioner of Education and using the ECUBE program (ECUBE Newsletter, Feb.1, 1974) produced some interesting findings. Setting back thermostats from a normal daytime setting of 75^0 to 70^0 would reduce fuel consumption by 17.1% annually. An addition setback for nights to 65^0 would produce an additional saving of 8.5%. If the school analyzed had been built facing north-south instead of its present east-west, 3% less fuel would be consumed on an annual basis. Analyses such as this measuring the effects of additional insulation, storm windows and other energy saving devices can also be performed. Such analyses can provide data to demonstrate the reduced cost of operation to accompany the installation of these energy saving devices. This data is mandatory if corrective measures are to be incorporated on existing buildings.

CONCLUSIONS

In conclusion, certain facts should be evident. First, an "energy crisis" does exist and a major waste of energy occurs in buildings of different types. Secondly, good design can reduce the amount of energy that is wasted in buildings. Thirdly, methods are available that will allow the architect or engineer to predict the energy consumption in a proposed building and can also evaluate proposed design or material modifications. Fourthly, more research is needed to allow maximum utilization of these prediction techniques and to ensure that energy conservation measures do not sacrifice esthetic or human values. The combination of these factors produces a major challenge to architects, engineers, and others presently concerned with the built environment.

REFERENCES

ASHRAE Handbook of Fundamentals, American Society of Heating, Refrigeration and Air-Conditioning Engineers, Inc., New York, New York, 1973.

Candill, Wm.W; Frank D. Lawyer and Thomas A. Bullock; A Bucket of Oil: The Humanistic Approach to Building Design for Energy Conservation, Cahners Publishing Co., Inc., 89 Franklin Street, Boston, Mass. 02110, 1974.

Chase, Maryellen, Editor; ECUBE Newsletter, American Gas Association, 1515 Wilson Boulevard, Arlington, Virginia 22209; published monthly.

Kusuda, Tamomi; NBSLD-Heating and Cooling Load Calculation Programs, National Bureau of Standards, U.S. Department of Commerce, Washington, D.C., 1974.

Meadows, Donella H., et.all., The Limits to Growth: A Report for the Club Rome's Project on the Predicament of Mankind; New York, N.Y., Universal Books, 1972.

Mitalas, G.P. "An Experimental Check on the Weighting Factor Method of Calculating Room Cooling Load", ASHRAE Transactions, 1969.

Mitalas, G.P. and D.G. Stephenson, "Room Thermal Response Factors", ASHRAE Transactions, Vol. II, 1967.

"Pattern of Energy Consumption in the United States", Stanford Research Institute Report, Stanford, California, 1973.