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Computer-aided building energy analysis techniques

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Abstract

Buildings are slowly replacing long-term investments that consume a lot of energy. Given current economic, as well as environmental constraints on energy resources, the energy issue plays an important role in the design and operation of buildings. Careful long-term decisions in the design and operation of buildings can significantly improve their thermal performance and thus reduce their consumption of energy. Alternative building design strategies, standards compliance and economic optimization can be evaluated using available energy analysis techniques. These range from simplified manual energy analysis methods for approximate energy use estimates to detailed computerized hourly simulation. The availability and ease of use of today's computers make them effective tools in the decision-making process of building design. This paper reviews the most common building energy analysis techniques and the potential applications of computer technology in the energy simulation and optimization of buildings. © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction

The three world primary economic sectors of energy use are industry, transportation, and buildings. Buildings have a substantial share of the energy consumption all over the world which deserves to be looked at carefully for the efficient operation of such facilities. Many possible approaches are expected to appear to meet future energy developments related to each of these sectors of energy use. Changes in energy resources and prices are associated with changes in productivity growth. This will lead people not only to use less energy, but also to produce new systems that consume less energy.

In the industrial sector, for example, the continued transition from labor-intensive heavy industries toward high technology electronics and computer-controlled industry will become the norm. This will help to create better productivity and product quality in the future, which might balance the slowdown that usually results from higher energy prices. In the transportation sector, primary attention is more likely to be focused on new technologies to produce more energy-efficient automobiles and transportation systems for optimum performance. But such strategies as mass transit, ride sharing, and moving closer to places of work, could be regarded as a public reaction to unpredicted increases in energy costs, as well as the associated environmental impacts.

In the building sector, efforts toward designing and operating energy efficient buildings will continue. One measure of energy conservation may be in the shift in resource allocation, such as reducing the space air-conditioning load by the designing and using of climate-responsive buildings and materials, or constructing compact and tight building envelopes. This will be associated with the development and use of energy-efficient equipment.

Technological advances in building structural systems and materials, heating, air-conditioning, lighting and other human comfort-designed systems, as well as human needs and requirements for new spatial arrangements, new building types and the associated costs all lead to the necessary integration of building technology and aesthetics with the function of buildings. The increasing costs of energy and the environ-

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mental impact of the various sources of energy make optimum energy use a major objective in the design and operation of contemporary buildings. Therefore, performing the necessary energy analysis can help designers reach guided solutions in building design/operation decisions. Various building energy-analysis methods are available, ranging from simplified manual methods to detailed hourly computerized programs.

2. Building design and energy

Different interrelated issues influence building design, and combinations of these different issues determine the choice of building components. The energy issue can play a significant role in the building design process. As climate modifiers, buildings are usually designed to shelter occupants and achieve thermal comfort in the occupied space backed up by mechanical heating and air-conditioning systems as necessary. Significant energy savings can be realized in buildings if they are properly designed and operated. Energy awareness and energy management are important measures during the life of the building. However, as the saying goes, "prevention is better than cure". Therefore, building designers can contribute to solving the energy problem if judicious early design decisions are made regarding the selection and integration of building sub-systems.

Proper building design can reduce reliance upon supplemental mechanical heating and air-conditioning systems to achieve thermal comfort. The requirements for such systems depend on the function and schedule, as well as the climate that influences the thermal performance of the building and its design. The function and schedule of the building are operational parameters over which designers have little control. The climate, however, can only be modified by the designer through proper selection and integration of the building's physical components throughout the design process.

However, careful long-term decisions in the design and operation of buildings can significantly improve their thermal performance and thus reduce their consumption of energy. The impact of decisions on the thermal performance of a building diminishes along the different stages over its life as illustrated in the generic curves of Fig. 1. Design decisions made during earlier phases of the design process cost less and have a more significant impact on the performance of the building. Architects are accustomed to making their decisions based on personal experience. However, as much as experience is necessary, reliance upon an individual's experience alone may lead to inaccurate and inefficient decisions. The complexity of problems associated with contemporary buildings and the many variables and interrelations that link them cannot adequately be penetrated by a series of implicit evalu-

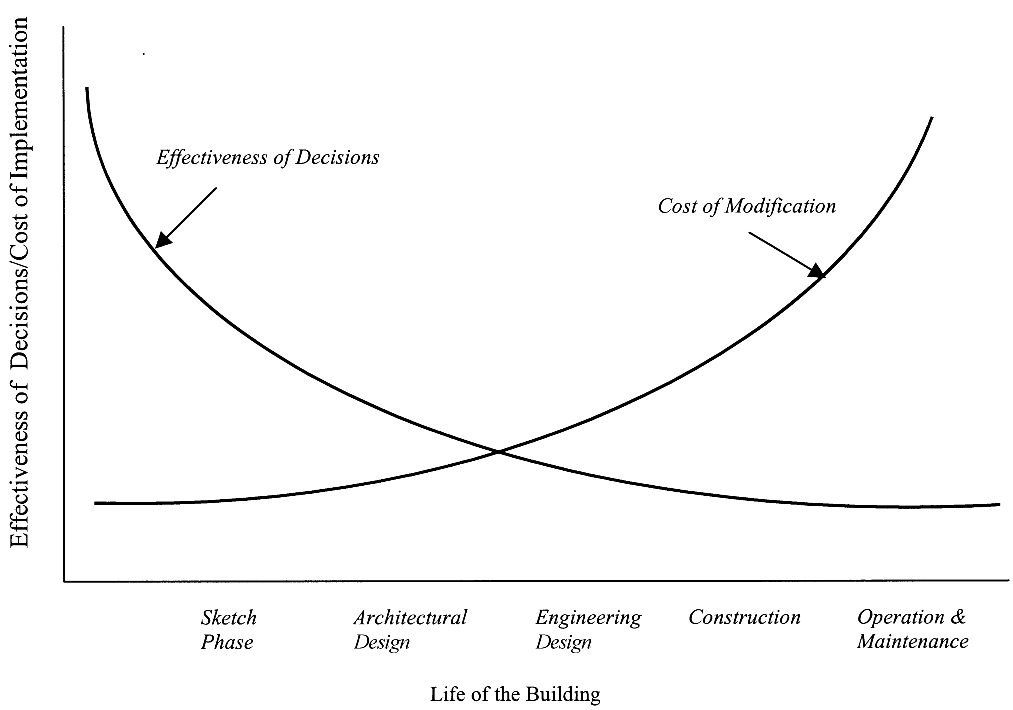

Fig. 1. Decision costs and their impact on the performance of a building through the various stages of its life.

ations. Such approaches tend to produce deficient buildings in too many aspects [16].

"In attempting to cope with the problems of present-day buildings, architects have sought to expand the amount and kind of information at their command. The behavior of structures, operation of mechanical systems, effect of micro climates, physical, as well as social and perceptual behavior and requirements of people, urban configuration and development — all have been grist to the architectural mill. It has been found that a host of factors, once not even considered, must be taken into account in the designing of buildings. And, with the advanced technology, knowledge, and living standards, their number is continually being augmented. All these additions to the architectural repertoire can greatly improve the effectiveness of architectural solutions, and have in fact done so" ([16], p. 3).

3. The role of computers in building design

The advancements in computer technology, as well as the ease and economy of their use, make computers an acceptable and frequent tool in the design of buildings and the evaluation of their performance. Computer graphics is one of the most visible manifestations of computers in architectural practice. Computer-Aided Design and Drafting (CADD) tools have become attractive to building designers because they allow flexibility, economy, speed and ease of re-use. They also provide designers with a practical view of reality through the use of color rendering and three-dimensional (3-D) animation.

The accuracy and speed of computers also make them an important contributor to the engineering aspects of the building design process. They can do most of the manual calculations in a very accurate and rapid manner which has contributed to the introduction of new approaches in building design. Therefore, computer models are widely used in the design and operation of buildings. Energy simulation models, for example, are effectively used for the design and prediction of building thermal performance. Optimization models, although not frequently utilized in the thermal design of buildings, are frequently used for decision-making purposes in other aspects of building design such as structural design and space layout and planning. The complexity of building systems and their ill-defined nature, as well as their dynamic thermal behavior, were among the factors for the limited use of optimization techniques into the overall thermal design of buildings. However, with the capabilities of today's computers, systematic approaches represented by optimization models are becoming more feasible and practical to achieve in the overall thermal design of buildings.

4. Why building energy analysis?

The complexities in contemporary buildings, the harsh climatic conditions of many parts of the world, and the increase use of office equipment and computer-intensive operations with a lot of internal heat generation make the use of air-conditioning a prerequisite to operate thermally comfortable buildings. The reliance upon mechanical air-conditioning systems requires a lot of energy, which necessitates strenuous efforts from building designers and operators in optimizing the thermal performance of such buildings. Energy analysis of buildings is carried out to achieve the following:

1. Evaluation of alternative designs, systems, subsystems, components.
2. Allocation of annual energy budgets.
3. Compliance with energy standards.
4. Economic optimization.

The need for building energy analysis in buildings can be summarized as follows:

- Buildings are replaced very slowly and decisions made on the design and selection of components will last for a long period of time.
- Early design decisions are the most effective and the cost of making changes to improve the thermal performance of buildings at later stages in their life is high and sometimes not effective.
- Many buildings cannot be operated without mechanical air-conditioning and ventilating systems to control the indoor conditions and an assessment of the required energy to operate them would be necessary.
- Energy prices are not stable and proper analysis and design can facilitate early investment returns.
- Buildings are large consumers of energy and therefore prime candidates for conservation efforts which can only be evaluated through proper energy analyses.
- Conservation is the best approach to reduced energy use. It helps extend the life of existing energy resources, has less environmental impact, and reduces the cost of energy production, as well as consumption. Alternative building energy conservation measures cannot be evaluated without proper energy analysis.

5. Building energy analysis methods

There are two basic levels of building energy analysis tools. These are simplified energy calculations and detailed energy calculations. The selected method and/or program of analysis should satisfy project requirements. Many factors are usually considered when selecting an energy analysis method/program. Such factors include [2]:

- Accuracy.
- Sensitivity.
- Speed and cost of learning and use.
- Reproducibility.
- Ease of use and level of detail (i.e. complexity of the input procedure).
- Availability of required data.
- Quality of the output.
- Stage of the project.

Even in the age of hi-tech computer technology and speed, simplified energy analysis methods, such as those based on the concept of degree–day and balance point temperature remain valuable tools. If the purpose of building energy analysis is to study trends, compare systems or alternatives, then simplified analysis methods may be appropriate. However, for a detailed energy analysis of building energy systems and sub-systems and life cycle cost analysis, more comprehensive tools will be required.

The following is an overview of some of the commonly used energy estimating methods, some of which use single measures, and others which utilize multiple measures where more than one index is analyzed.

5.1. Degree–day method

The degree–day method is a single-measure steady-state method suitable for heating energy consumption estimates of small buildings. Such calculations are simple enough to be carried out by hand. However, simple computer programs are also used to conduct the calculations. Although energy estimates from degree–day calculations are approximate, they help to give an idea about the energy consumption trends for small buildings.

This procedure is based on the assumption that, on a long-term average, solar and internal gains will offset heat loss when the mean daily outdoor temperature is 18.3°C (65°F), and that energy consumption will be proportional to the difference between the mean daily temperature and 18.3°C (65°F). Degree–days can be used to characterize the severity of a climate and is very useful in energy estimate calculations for comparing the heating requirements from one location to another.

$$DD_{\mathrm{m,\,h}} = \sum_{d=1}^{D_{\mathrm{m}}} (18.3 - \bar{T}_{\mathrm{A}})^{+} \tag{1}$$

The heating energy required is:

$$E = \frac{24 \cdot HL \cdot DD_{\mathrm{h}}}{\Delta T_{\mathrm{des}} \cdot \eta \cdot V} \tag{2}$$

or:

$$E = \frac{24 \cdot UA_0 \cdot DD_{\mathrm{h}}}{\eta \cdot V} \tag{3}$$

where $DD_{\mathrm{h,m}}$ is the heating degree–days for month m, D_{m} is the number of days per month, $\bar{T}_{\mathrm{A}}$ is the daily average ambient temperature $=(T_{\mathrm{max,d}} - T_{\mathrm{min,d}})/2$, E is the heating energy usage (fuel requirements) for the estimated period, HL is the design heat loss based on T_{des}, including infiltration, W, DD_{h} is the heating degree–days, based on 18.3°C (65°F) balance temperature for the estimated period, ΔT_{des} is the design temperature difference ($T_{\mathrm{R}} - T_{\mathrm{A}}$), K, η is the correction factor: efficiency of equipment (rated full load) $\eta = 1.0$ for efficiency of 100%, V is the heating value per unit of fuel as in Table 1, UA_0 is the building area-conductance product, often called "Building Loss Coefficient (BLC)", W/K (this term includes infiltration) and the $+$ sign indicates that only positive values are added.

This means that once the design heating load or the overall building loss coefficient is determined, annual heating energy requirements can be estimated based on the number of heating degree–days at the analyzed location.

5.2. Modified degree–day method

Due to the inaccuracy of the results obtained using the 18.3°C (65°F) fixed-base degree–days, a correction factor, C_{D}, is utilized. This is an empirical correction factor for the heating effect of the 18.3°C (65°F) degree–days. This factor was introduced by electric utilities to correlate the measured data of electrically heated houses in mild climates to estimates based on the degree–day method. Therefore, Eqs. (2) and (3) become:

Table 1
Typical fuel heating values

Fuel	Heating value ($\mathrm{MJ/m^3}$)	
Natural gas	39	(1050 $\mathrm{Btu/ft^3}$)
LP gas (propane)	25	(90,000 Btu/gal)
No. 2 fuel oil	39	(140,000 Btu/gal)
Electric		3413 Btu/kWh

$$E = \frac{24 \cdot HL \cdot DD_{\mathrm{h}}}{\Delta T_{\mathrm{des}} \cdot \eta \cdot V} C_{\mathrm{D}} \tag{4}$$

or:

$$E = \frac{24 \cdot UA_0 \cdot DD_{\mathrm{h}}}{\eta \cdot V} C_{\mathrm{D}} \tag{5}$$

where C_{D} is an empirical correction factor for heating efficiency versus degree–days (function of outdoor design temperature) and $C_{\mathrm{D}}=1$ if DD are based on actual $T_{\mathrm{Bal}}=0.77$ if 18.3°C (65°F) is arbitrarily used as the balance temperature.

However, the degree–day approach has the following shortcomings:

1. It is only good for heating.
2. There is no precise consideration of internal heat gains. Applicability is limited to residential buildings and similar skin-load dominated structures where envelope transmission and infiltration are the load dominating factors.
3. It is conservative. With better insulation levels and increased internal loads results can be overestimated and C_{D} utilized.
4. It is based on average conditions and does not account for day-to-day weather variations nor for the effect of temperature on equipment performance.

5.3. Variable-base degree–day method

Traditionally, 18.3°C (65°F) used to be the base temperature for calculating heating degree–days. However, the actual balance temperature of the house depends on many factors, such as the type and quality of construction, the level of insulation used, the internal and solar heat gains, the thermostat setting, as well as the behavior of the occupants, all of which vary from country to country, from region to region, and even from house to house within the same locality. All these factors make the use of the 18.3°C base temperature inaccurate and unreliable. Therefore, one single balance point temperature is clearly not enough, and the need for variable base temperatures becomes a virtual necessity for the purpose of simplified energy calculations in buildings.

The variable-base degree–day method is a generalization of the widely used *DDM*. It retains the familiar degree–day concept, but counts degree–days based on the ***balance point temperature*** for the building, which is the outdoor temperature at which neither heating, nor cooling is required. At this temperature the internal and solar gains offset the losses from the structure of the building. Heating is required only when $T_{\mathrm{A}} \angle T_{\mathrm{Bal}}$.

An instantaneous steady-state energy balance on the building yields:

$$0 = UA_0(T_{\mathrm{R}} - T_{\mathrm{Bal}}) - g \tag{6}$$

which in turn yields:

$$T_{\mathrm{Bal}} = T_{\mathrm{R}} - \frac{g}{UA_0} \tag{7}$$

where g is the solar and internal heat gains and T_{R} is the desired room temperature.

For an average period of one month, the average hourly rate of solar and internal heat gains over the month, $\bar{g}$, is used and the monthly average balance temperature becomes:

$$T_{\mathrm{Bal}} = T_{\mathrm{R}} - \frac{\bar{g}}{UA_0} \tag{8}$$

When different balance temperatures are experienced over the day and night due to changes in the operation of the building or thermostat settings, the heating degree–days for the month m and period (shift) i, $DD_{\mathrm{hm},i}$ can be obtained as:

$$DD_{\mathrm{hm},\, i} = \sum_{d=1}^{D_{\mathrm{m}}} (T_{\mathrm{Bal},\, i} - \bar{T}_{\mathrm{A,\, d}})^{+} \tag{9}$$

The total heating energy required can be given as:

$$Q_{\mathrm{htg,\, sys}} = 24 \sum_{i=1}^{n} UA_0 f_i DD_{\mathrm{hm},\, i} \tag{10}$$

Then the heating energy used will be:

$$E = Q_{\mathrm{htg,\, sys}}/\eta_{\mathrm{h}} \tag{11}$$

where n is the number of operating periods (shifts), f_i is the time fraction for the period i out of 24 h ($N_i/24$) and η_{h} is the heating system efficiency.

The cooling degree–days for month m and period i, $DD_{\mathrm{cm},i}$, can also be estimated in a similar manner as:

$$DD_{\mathrm{cm},\, i} = \sum_{d=1}^{D_{\mathrm{m}}} (\bar{T}_{\mathrm{A,\, d}} - T_{\mathrm{Bal},\, i})^{+} \tag{12}$$

The total cooling energy required, Q_{clg} , can be given as:

$$Q_{\mathrm{clg}} = 24 \sum_{i=1}^{n} UA_0 f_i DD_{\mathrm{cm},\, i} \tag{13}$$

This cooling energy calculation applies to buildings with a constant UA_0 where ventilation is not introduced and windows and other openings are assumed to be kept closed. However, during the intermediate or cooling season, natural or fan-powered ventilation can be utilized to eliminate heat gains and postpone mechanical cooling. Therefore, mechanical air-conditioning will be needed only after the outdoor temperature exceeds a certain maximum temperature, T_{Max}, which corresponds to a building heat loss coefficient, $UA_{0,\max}$, that considers open windows for ventilation such that [2]:

$$T_{\max} = T_{\mathrm{R}} - \frac{\bar{g}}{UA_{0,\ \max}} \tag{14}$$

Therefore, the number of cooling degree–days based on T_{Max} becomes:

$$DD_{\mathrm{cm},\ i(T_{\max})} = \sum_{i=1}^{n}\sum_{d=1}^{D_{\mathrm{m}}}(\bar{T}_{\mathrm{A,\ d}} - T_{\max\ ,\ i})^{+} \tag{15}$$

and the total cooling energy required is given as:

$$Q_{\mathrm{clg}(T_{\max})} = 24UA_0\left\{\sum_{i=1}^{n}[f_i DD_{\mathrm{cm},\ i(T_{\max})}] + [(T_{\max} - T_{\mathrm{Bal}})N_{\mathrm{d,\ max}}]\right\} \tag{16}$$

where $N_{\mathrm{d,max}}$ is the number of days in the cooling season with $\bar{T}_{\mathrm{A}} > T_{\mathrm{Max}}$.

Latent cooling loads can be estimated on a monthly basis by adding the following term to the cooling energy requirement equation:

$$Q_{\mathrm{latent}} = 3010\dot{V}(\bar{w}_{\mathrm{o,\ m}} - \bar{w}_{\mathrm{i,\ m}}) \tag{17}$$

where Q_{latent} is the monthly latent cooling load, W, $\dot{V}$ is the monthly infiltration, l/s, $\bar{w}_{\mathrm{o,m}}$ is the monthly average outdoor humidity ratio, $\mathrm{kg_w/kg_{dry\ air}}$ and $\bar{w}_{\mathrm{i,m}}$ is the monthly average indoor humidity ratio, $\mathrm{kg_w/kg_{dry\ air}}$.

Generally, cooling energy calculations based on degree–days are more difficult than for heating. Heat gains, ventilation rates, and occupants' behavior in operating windows and air-conditioning vary. Fan energy for fan-powered ventilation must also be included. Humidity effects and interrupted operation also need to be carefully considered. This is especially more critical during mild weather when T_{A} is close to T_{Bal} where greater uncertainty is expected [2].

Despite these limitations, the variable-base degree–day method can give accurate annual heating energy estimates especially for skin-load dominated buildings. It improves the accuracy of the traditional fixed-base degree–day approach while maintaining its simplicity and ease of use. This method has been proven to yield annual residential energy consumption estimates comparable to those obtained from more detailed analysis approaches [6].

5.4. Bin method

For buildings where internally generated loads dominate or where cooling loads are not linearly dependent on the outdoor/indoor temperature difference, such as large commercial buildings, the single measure degree–day approach is not sufficient. Mass effects, cooling energy, humidity, and solar effects, as well as equipment efficiencies and part load performance are not taken care of by the single-measure degree–day approach. Therefore, multiple measure methods need to be utilized.

The bin (or temperature frequency) method consists of performing instantaneous heating and cooling energy calculations at many different outdoor dry bulb temperature conditions (bins), and multiplying the results by the number of hours of occurrence of each condition (bin). The bin method is characterized as follows:

1. It is good for heating and cooling energy calculations.
2. Bins are temperature bins, usually 2.8°C (5°F) in size normally with three daily 8-h shifts with the number of hours of occurrence for each bin.
3. The mean coincident wet-bulb temperature for each bin is used to calculate ventilation and infiltration latent loads.
4. The method takes into account both occupied and unoccupied conditions and accounts for internal loads through building balance point adjustments.
5. It is useful for the analysis of individual systems, equipment, etc.
6. It accounts for the part load performance of HVAC equipment.
7. It is based on hourly weather data rather than daily averages, and is therefore, more accurate than the degree–day method.

The consumption is calculated for each bin outdoor temperature and multiplied by the number of hours of occurrence for that bin as [2]. The following equation (18) uses T_{A} for the shift in question, as opposed to $T_{\mathrm{A,d}}$ (average daily) used in degree–day evaluation:

$$Q_{\mathrm{htg}} = UA_0\sum_{j=1}^{n}N_{\mathrm{bin},\ j}(T_{\mathrm{Bal},\ j} - T_{\mathrm{A},\ j})^{+} \tag{18}$$

The heating energy used will be:

$$E = Q_{\mathrm{htg}}/\eta_{\mathrm{h}} \tag{19}$$

where n is the number of bins, $N_{\mathrm{bin},j}$ is the number of hours of occurrence of the jth bin and $T_{\mathrm{A},j}$ is the outdoor ambient temperature at the jth bin.

5.5. Modified bin method

The bin method can be used for cooling energy requirements. However, it only uses peak loads to establish a load profile as a function of outdoor dry-bulb temperature. Therefore, a more refined load profile that accounts for off-design conditions based on diversified, rather than peak loads, is of greater use.

The diversified load profile is characterized by average solar gain profiles, average internal (people, lights and equipment) profiles, and cooling load temperature difference (CLTD) values. The development of each load component as a linear function of outdoor temperature allows the combination of these individual components into a total load profile for both summer and winter conditions, as well as the determination of the balance point temperatures [23].

Normally, most buildings operate on at least two shifts requiring at least two calculations representing occupied and unoccupied hours. Also, some buildings require heating in some parts and cooling in other parts. In such situations, building energy calculation by zone is required to avoid cancellation of combined heating and cooling energy requirements of different zones, which does not represent reality [23].

The modified bin method, which is explained in more detail in other sources [19,23,31] overcomes most of the shortcomings of the single measure methods. It gives reasonable monthly and annual building energy estimates in a simpler manner than detailed hourly simulation programs. Reasonable results are obtained for low mass and internal load dominated (ILD) buildings in particular. However, when solar effects and thermal mass dominate the analysis, the method should be used with caution [6]. This method is suitable for buildings between 500 and 2500 m^2.

The analysis can be conducted manually, however, computer programs exist for bin method energy calculations. ASEAM (A Simplified Energy Analysis Method) is a public domain program written in BASIC that uses ASHRAE's modified bin method for calculating the energy consumption of residential and simple commercial buildings. ASEAM requires information on the design of the building and uses standard algorithms to calculate both zone and building peak loads, as well as automatic sizing of the equipment based on the calculated loads. Life cycle cost analysis is also incorporated within the program. Different output reports can be obtained, including building energy performance standards (BEPS) reports for each run [12].

5.6. Detailed building energy and systems simulation

A model is a representation of reality where an assumed real system is abstracted from the real system represented by the dominant factors and implemented using reasonable assumptions [27]. Simulation models are flexible performance tools that can be used effectively for analyzing the behavior of systems. A simulation model is normally used to produce a set of selected measures that reflect the performance of the simulated system. In simulation models, the relationships between input and output are implicitly expressed through model sub-systems that are logically linked to one another.

In building design, simulation models are used to evaluate the performance of building systems with given predetermined values for the associated design variables. A great deal of information can then be obtained for evaluating the performance of the building system under given conditions. There are mainly two modeling strategies commonly used in known building energy simulation programs. These are the sequential approach [referred to as the Load, System, Plant, and Economics (LSPE) sequence], and the simultaneous solution approach.

In the sequential approach shown in Fig. 2, the heating and cooling loads are first calculated for each space for the whole year. This is followed by the secondary system simulation where the required energy flows at the air handling units or other equipment supplied by the central plant are calculated. Then the central plant is simulated in order to determine the source energy requirements. This is followed by calculations of the source energy cost or life cycle cost analysis. The output of each step is used as an input to execute the next step. The calculations are normally carried out on an hourly basis in order to account for variations in weather and occupancy conditions.

This approach saves computer time and memory. It can be satisfactory if the equipment has enough capacity to meet all air-conditioning loads. However, it lacks interaction between load, system and plant, which could produce questionable results, especially when equipment capacity cannot meet required loads and unmet loads can only be reported.

As a result, the simultaneous modeling approach was introduced to account for such load–system–plant interaction. In this approach, the load, system and plant models are solved simultaneously at each time step (each hour) as shown in Fig. 3. This procedure improves modeling accuracy, but only at the cost of more computer memory and time.

In the load modeling step, the most commonly used approaches are the weighting factors and the heat balance methods. In the weighting factors method, heat gains to building spaces are converted to cooling or heating loads on the air using pre-calculated "weighting factors" [30]. The heat gain weighting factors are a set of parameters that quantitatively determine the stored amount of the energy

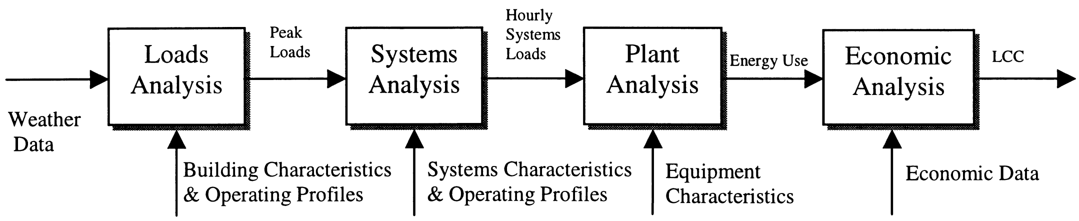

Fig. 2. Sequential simulation approach.

entering the space and how rapidly this stored energy is released during later hours. This method represents a compromise between simpler methods that ignore building mass effects such as steady-state methods, and the more complex methods, such as complete heat balance calculations [2].

One set of weighting factors is determined by the heat balance equations and then used during the entire simulation period. The system properties of factors influencing the weighting factors are assumed to be constant (not a function of time) and linearization of processes is commonly used for simplifications [2].

The best known example of the above is the DOE-2 program produced by the US Department of Energy which is a public domain program that can be used for analyzing the energy behavior of buildings and their associated heating, ventilating and air-conditioning (HVAC) systems. DOE-2 utilizes hourly weather data to calculate the hour-by-hour performance and response of a building with a known description. It can also provide users with an economic analysis of the energy use and the costs and benefits of altering the design [21]. Further developments and updates of the DOE-2 program have continued since the first version. Each new version of the program is denoted by appending numbers and letters for major and minor changes, respectively [6]. Several microcomputer based versions of the DOE-2 program with a user-friendly interface have been developed by various private organizations.

DOE 2.2 is the most recent updated version of the program. This version is well documented with enhanced modeling capabilities. These include combined HVAC system and plant simulation programs, new equipment selection, enhanced air handling equipment simulation capabilities, improved scheduling capabilities, improved lighting system description, multiple lighting and equipment profiles and a more general library features for various building components. Up to 100 sites, building and sub-building electric and fuel meters are allowed with separate and combined summary and hourly report capabilities [18].

In the heat balance method, on the other hand, a detailed heat model of the thermal transfer processes in the rooms is used to calculate loads from heat gains. The net instantaneous heating and cooling loads are calculated on the space air mass. A set of equations for each enclosing surface and room air are solved for the unknown surface and air temperatures. Based on these temperatures, the convective heat flow to or from the space air mass is calculated. This method requires fewer assumptions than the weighting factors method [2].

The best known example is the Building Load Analysis and System Thermodynamics (BLAST) simulation program which was first developed by the US Army Construction Engineering Research Laboratory in 1977. The BLAST program has been supported and maintained by the BLAST Support Office at the University of Illinois at Urbana-Champaign since the year 1983. It was developed for predicting energy consump-

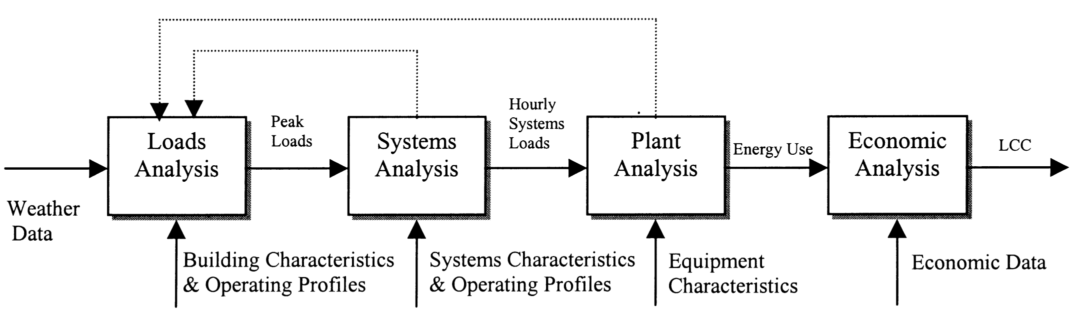

Fig. 3. Simultaneous simulation approach.

tion and systems performance and costs of new or retrofit building designs of different types and sizes. Hourly building energy analyses for mechanical equipment design as well as checks for compliance with design energy budgets can also be obtained [4].

Generally, the weighting factors method is the faster of the two, but the heat balance method is more accurate. However, given the speed and efficiency of contemporary computers, the heat balance method is more flexible and will probably be the ultimate choice [30].

Both DOE-2 and BLAST programs are whole-building energy simulation programs supported by the US government in order to promote energy efficiency. Each of these two programs has its strengths and weaknesses. Recent efforts are underway at LBNL in taking the best features and capabilities of BLAST and DOE-2 and combining them in a new program called EnergyPlus. The building simulation of the new program will be based on a heat balance engine with HVAC systems integrated into the building simulation. Many new building technologies and building and systems simulation models will be accessible with the new program which represents a significant step towards next-generation building energy simulation programs, both in terms of computational techniques, as well as program structure [25].

HVAC secondary systems components transfer energy between the building and the central plant and only a few of these components consume energy directly (e.g. fans and pumps). The secondary HVAC system includes distribution components (fans/pumps, ducts/pipes, dampers/valves, plenums/headers, fittings, etc.) and heat and mass transfer components (heating, cooling and dehumidifying coils, heat exchangers, evaporative coolers, steam injectors, etc.) [2]. In most whole-building simulation programs, common secondary systems are provided to the user through a fixed selection menu. Modeling of secondary systems is based on mass, energy, and moisture balances at various components (coils, fans, etc.) and junctions (mixing boxes, diverters) in the distribution system [30] for the calculation of the required rate of energy delivery to these components to meet the space load determined in the load model.

The primary system equipment includes chillers, boilers, cooling towers, cogeneration equipment, and plant-level thermal storage equipment. This equipment delivers heating and cooling to a building, usually through secondary systems and this represents the major energy-consuming component of a building [2]. Part load conditions performance of these systems is necessary to estimate their energy usage. Although detailed physical representation of the primary equipment is available, central plant equipment is most often modeled by curve fits of manufacturer's data to relate the primary fuel and electricity energy input rate to the secondary systems required energy rates [6,30].

Improved system simulation is achieved using component-based simulators, of which TRNSYS is the best known example. TRNSYS, which is a transient system simulation program, was developed at the Solar Energy Laboratory [29] at the University of Wisconsin-Madison in the mid-1970s for the analysis of active solar heating and cooling systems. The TRNSYS program is written in FORTRAN with a modular structure that allows for the addition of new mathematical models. It is intended for analyzing the transient behavior of systems [12]. Such component-based simulation programs are most useful for detailed studies of special systems, such as solar heating and cooling systems, but not for detailed simulations of multi-zone buildings for year-long periods [30]. Simulation with sub-hourly time steps can be used in the program.

Many other simpler microcomputer-based building energy simulation programs are available with different capabilities and sophistication. An example is ENER-WIN [11], developed at Texas A&M University. This whole-building energy simulation program is written in FORTRAN and estimates the annual energy performance of buildings, including daylighting, demand charges, life-cycle costs, and floating temperatures in unconditioned zones. The input includes graphic entry of building plans through a sketch interface, building envelope thermal properties, hourly use profiles and indoor temperature settings. Tabular reports and graphics output can be obtained for monthly and annual loads and energy, peak loads, electric displacement by daylighting, life-cycle costs, and weather summaries [11].

The greatest advantage of detailed energy simulation models is realized mostly in simulating the behavior of large and complex systems to provide detailed information on their performance. Although these programs can provide extensive hour-by-hour simulation of the building heating and cooling systems with different output options including life cycle cost analysis, they require some time in learning how to use them, preparing the input, running them and interpreting the results with a different degree of difficulty for each program.

Most building energy simulation programs are concerned with whole-building energy use estimates. However, the accuracy of such programs depends on the accuracy of modeling building components (envelope components, infiltration, internal gains, and inter-zonal heat and mass transfer and systems components). Their accuracy is also highly dependent on the program input assumptions which include:

- Weather data used.

- Tabulated engineering values.
- Interpretation of building drawings and specifications.
- Operational profiles.
- Verification of input data.
- Experience of the user (different program users end with different results).

Therefore, part of the inaccuracy in the simulation results are sometimes attributed to the users of such programs rather than the analysis methods themselves.

6. Systems approach

Technological advances in building structural systems and materials, heating, air-conditioning, lighting and other human comfort-designed systems, as well as human needs and requirements for new spatial arrangements and new building types and the associated costs, all lead to the necessary integration of building technology and aesthetics with the function of buildings. "Because the totality with which architecture is concerned is not one undifferentiated whole, it can be grasped only by understanding its parts, and, because these are numerous, by rationally ordering them in relation to each other and to the system as a whole" ([16], p. 4).

Building design is a process that should be thought of as a whole with an interrelation of parts acting together to achieve desired objectives and is more than just a simple addition of these parts. Therefore, the total integration of these parts and their associated variables is necessary for better and efficient solutions to architectural problems.

A building consists of many sub-systems that interact with each other to determine the performance of the building as a whole system. Changing any of these sub-systems or the relationships that link them affects the performance of the whole system. Defining the building as a system, a collection of parts that are arranged in a way to act as a whole, and dealing with it that way allows the implementation of systems analysis to effectively reach the solution to many architectural problems.

In order to reach such efficient solutions, there is a need for adequate information to guide building designers in the selection and handling of alternatives. This requires a clear definition of ill-defined architectural problems which designers presently lack.

A systems approach helps in reaching decisions that are optimum for the system as a whole through the division of complex systems into smaller and more manageable components that are logically linked to achieve defined objectives using logical and systematic procedures that can be explained and repeated. This approach is the main concern of the field of Operations Research. In building design a similar concern can be realized in designing buildings effectively to behave in a way that achieves the desired objectives for which they are intended.

Applying a systems approach implies the implementation of optimization techniques. Therefore, in optimization the best solution is sought that satisfies objectives from among a field of feasible solutions under the restriction of certain constraints. Optimization utilizes mathematical techniques to systematically model and analyze decision problems which is basically the focus of the field of Operations Research.

In optimization, decisions are made on certain quantitative measures to get the best course of action possible for a decision problem. To decide on how to design, build, regulate, or operate a physical or economic system using a systems approach requires three main elements ([3], p. 2; [27], p. 5).

1. Selection alternatives from which a selection is made (variables).
2. Accurate and quantitative knowledge of the system variables interaction (constraints).
3. A single measure of system effectiveness (objective function).

Although optimization models require a great deal of mathematics, creativity and imagination in formulating the problem and its implementation are as important for successful and effective utilization in practice. In order to make decisions using a systems approach, it is necessary to understand processes and to be able to control them. In order to understand processes, their inputs and outputs must be identified and the associated properties must be specified with a proper relationship that links them together. Criteria are also necessary to compare output to objectives which help in controlling the process [16].

Optimization does not require prior knowledge of the solution to the problem as is the case in simulation. However, optimization models have the disadvantage of difficult and sometimes impractical formulation of the problem into a mathematical model, especially ill-defined problems such as those encountered in architectural design where systematic approaches are not traditional practice.

7. Optimization in building design

The diverse specialties in the design of buildings participated in the introduction of experience from other fields such as optimization techniques introduced by engineers for building structural and mechanical systems design. The non-numerical and ill-defined, as well as multi-criteria nature of many architectural problems, have contributed to the difficulty in formulating them in the systematic approaches framework.

Even though the use of mathematical models in building design is relatively new, application of optimization techniques in different building design problems has taken place over the past 30 years. Such applications range from spatial allocation problems as well as site developments and land use to the design of structural and mechanical systems, in buildings with these achieving different degrees of success.

The most common architectural problem for which an early application of optimization techniques took place was that of spatial arrangement in buildings. Many optimization models were developed to aid designers in the layout of spaces [13] and allocation of activities within spaces for small and multi-story buildings [22,5]. The basic objective for these models is to minimize the total communication cost between spaces and the allocation of their activities.

An integrated approach for the environmental design of buildings can be achieved by applying optimization techniques to their environmental performance. However, integration of all building environmental parameters can be a difficult and complex problem, and an optimum thermal performance of buildings, for example, can be achieved by coupling a proper optimization technique to the thermal performance analysis of buildings. The interaction between different design variables helps not only to optimize energy use in buildings, but also to provide the designer with quantitative guidance on the likely best combination of building design variables for different building types in different climates.

Most previous efforts in the thermal design of buildings were directed to the development of simulation models as discussed earlier. However, the speed of today's computers and the availability of suitable energy simulation programs has allowed the integration of simulation models and optimization techniques within the thermal design of buildings for decision-making purposes.

Traditional practice in the thermal optimization of buildings has been followed in choosing the capital and operating cost as the criterion of optimization. Wilson and Templeman [28] described a model for determining the thermal design of an office building with minimum initial and operating costs. They used the total discounted cost of the entire heating and insulation process as the criterion of optimality. Based on that and applying geometric programming optimization, they developed a computer model given the designer an idea about the heating plant capacity and the optimum insulation along with the optimum cost. They assumed that the structure of the building had been designed, including the internal and external configurations. The sizes and thermal properties of wall, floor and partition materials, as well as the general desired thermal performance of the building and type of heating fuel used, were also assumed to be known [28]. These assumptions make their model of limited help in providing building designers with prescriptive information that is mostly needed in the early phases of the design process.

D'Cruze et al. [7,8] and Radford and Gero [26] developed an optimization model for early decision making of the design of parallel piped open-plan office buildings based on thermal load, daylight availability, net usable area and capital cost as the building performance multi-criteria of optimality. They used dynamic programming for building optimization over design variables of window geometry, wall and roof construction, building orientation, massing, floor area and building shape.

Tradeoff diagrams for the physical environment design in buildings were developed by Radford and Gero [26] utilizing the concept of Pareto optimality for building design as a multi-criteria optimization problem. They produced a visual solution in terms of tradeoff diagrams for the peak summer internal environmental temperature and the daylight factor criteria in the space.

Different optimization techniques were also utilized to optimize the use of insulation over the components of passive, as well as air-conditioned buildings, based on technical, as well as economical considerations. The common objective is to maximize net energy savings from using the proper amount and distribution of insulation over the building envelope [20].

Based on thermal discomfort as the criterion of optimality, Gupta [14] and Gupta and Spencer [15] described a model that uses a sequential simplex type of search procedure to optimize the thermal performance of buildings under periodic indoor and outdoor design conditions, using a typical outdoor weather cycle for summer in Australian cities, over several design variables.

A building thermal design optimization model, termed ENEROPT (ENERgy OPTimization), was developed by Al-Homoud [1] by integrating the optimization search technique of Nelder and Mead [24] and Himmilblau [17] with the ENERcalc microcomputer-based building energy simulation program developed at Texas A&M University. This hour-by-hour weather and building energy simulation model estimates the annual energy performance of buildings, including daylighting, as well as systems simulation. The simulation program incorporates an hourly simulation model that permits the simulation of less than full months and still maintains its statistical integrity for energy calculations. It allows the simulation of a full year (8760 h) or any multiple of seven days each month. The use of this abbreviated mode, in which as few as 2016 h are simulated annually, reduces the computer run time by 75% compared to that of other similar approaches [9,10]. This feature makes the program more efficient in optimization where hundreds of simulation runs need to be conducted to reach an optimum solution.

The simulation program is used as a subroutine in the optimization model that is called whenever a new value of the objective function has to be evaluated. Design variables that basically describe the thermal performance of buildings envelope components, shape and orientation can be optimized. The optimization is based on the minimum annual source energy utilization level and the minimum thermal discomfort criteria for air-conditioned and unconditioned building optimization, respectively.

8. Difficulties in using optimization in building design

The application of optimization to building design is relatively new and requires a careful formulation of the problem. Although there is a wide range of optimization techniques, not all of them are suitable for application into building design and the choice of the proper technique is not easy for such ill-defined problems. Many architectural problems are characterized by being constrained, multivariable optimization problems with non-differential objective functions and non-linear relationships. In addition to other obstacles, such problems contribute to some of the weaknesses and shortcomings of applying a formalized systematic analysis to the optimization of building design features. These difficulties can be summarized as follows:

1. Building design problems are characterized by being ill-defined problems, therefore requiring certain assumptions and compromises to formulate them (especially objective functions) as well-defined problems that are suitable for formalized systems approach applications.
2. The non-differentiable nature of objective functions in most building design problems and the difficulty in their formulation limit the choice of suitable optimization techniques. This contributes to the inefficiency and inaccuracy of some building design optimization models.
3. A building is characterized by being lost sight of as a whole in the production of its components. Therefore, certain compromises are expected to be made with an *approach* to the best solution rather than the best solution itself to be sought due to multiple objectives and conflicting goals in whole building design optimization.
4. A building as a system is composed of a number of components or sub-systems and an overall optimum solution of all building components is not possible. This can only be achieved through a series of separate optimum decisions for these sub-systems which sometimes would result in complicated formulations of the problem and an inability to reach a true optimum.
5. Some building design problems require discrete and discontinuous variables with non-linear relationships which is another limitation on the choice of proper optimization techniques.
6. Economic, social, technical, legal and aesthetic constraints tend to limit the range of desirable solutions. As a result, building performance outside the range of the given constraints, where the global optimum might lie, cannot be tested and only a local optimum might be reached.
7. Applying a systematic approach to building design would help provide the prescriptive information needed most, but would not eliminate the role of experience or common sense, nor replace the designer. However, most architects do not accept systematic methodologies in the design of buildings and believe in the uniqueness of each building.

9. Conclusions

An overview of available building energy analysis techniques has been presented. They range from simple steady-state methods to detailed hourly analysis techniques. The concept of simplified energy analysis remains a valuable tool even in the age of hi-tech computers. Detailed computer-aided building energy simulation and optimization techniques are effective tools that can be used as an aid to, not a replacement for, building designers in the decision-making process for standards compliance and for economic optimization.

Available energy simulation models are useful and powerful tools for the evaluation of the thermal performance of buildings. They can provide extensive *performance* information on the selected building considering the dynamic behavior of the system, as well as part load behavior (the effect of part load on equipment efficiency). Optimization techniques can also be useful in providing designers and decision makers with *prescriptive* information that cannot be easily achieved using simulation models alone. Future trends in computer-aided building energy modeling are expected to involve:

- More accurate models with greater flexibility.
- Shorter time steps.
- More user-friendly interfaces.
- Graphical representations.
- More comprehensive programs covering all users

needs.
- Interfacing with CADD packages.
- Design tools.
- More utilization of optimization techniques.

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