THE FRAMEWORK OF AN OPTIMIZATION MODEL
FOR THE THERMAL DESIGN OF BUILDING ENVELOPES

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ABSTRACT

Careful long term decisions in the design and operation of buildings can significantly improve the thermal performance and thus reduce the consumption of energy. The availability and ease of use of today's computers can be a significant benefit to the decision making process of building design.

In dealing with the building as a thermal system, the proper selection of its components and their relationships can be organized using a systems approach. This can be achieved by coupling an optimization technique into the thermal performance of buildings early in the design process. This requires formulating the building as a well-defined thermal system in a framework suitable for the application of systematic approaches. The aim of this paper is to describe the basic framework of a building thermal design optimization model by defining building design variables, a criterion of optimality, constraints, and a suitable thermal simulation model that can be integrated into the proper optimization technique.

INTRODUCTION

Buildings are usually designed to provide shelter as well as thermal comfort in the occupied space, backed up by mechanical heating and air-conditioning systems as necessary. The envelope of the building is a transition space through which interaction between indoor and outdoor environment takes place as shown in Figure 1. The selection and arrangement of building envelope components can significantly impact its thermal performance which is a determining factor in its consumption of energy.

Although selection of buildings' physical components, orientation and shape are early design decisions with the greatest impact on thermal performance, they are not usually considered in enough detail by designers at that stage of the design process. This is due, in part, to the lack of suitable design tools that can provide designers with the necessary prescriptive information. Most available energy analysis models are useful in evaluating thermal performance of buildings with prescribed solutions. Early design information, while having the greatest impact on buildings thermal performance (as shown in Figure 2), is not easily available.

It is an objective of the building designer to design a thermally optimum building with minimum reliance upon mechanical heating and air-conditioning systems sacrificing neither aesthetics nor function of the building. However, the range of design alternatives is wide which makes it difficult for the architect to decide on the best choice in the absence of enough design information and only by reliance upon experience.

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 buildings structural and mechanical systems design. The non-numerical and ill-defined, as well as the multi-criteria nature of many architectural problems have contributed to the difficulty in formulating them in 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 different degrees of success.

The most common architectural problem for which early application of optimization techniques took place is that of spatial arrangement in buildings. Many optimization models were

developed to aid designers in the layout of spaces (9) and allocation of activities within spaces for small and multi-story buildings (17,3) 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 employing 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.

Most of the efforts in the thermal design of buildings were directed to the development of simulation models (16). However, the speed of today's computers and the availability of suitable energy simulation programs allowed the integration of simulation models and optimization techniques to the thermal design of buildings for decision making purposes.
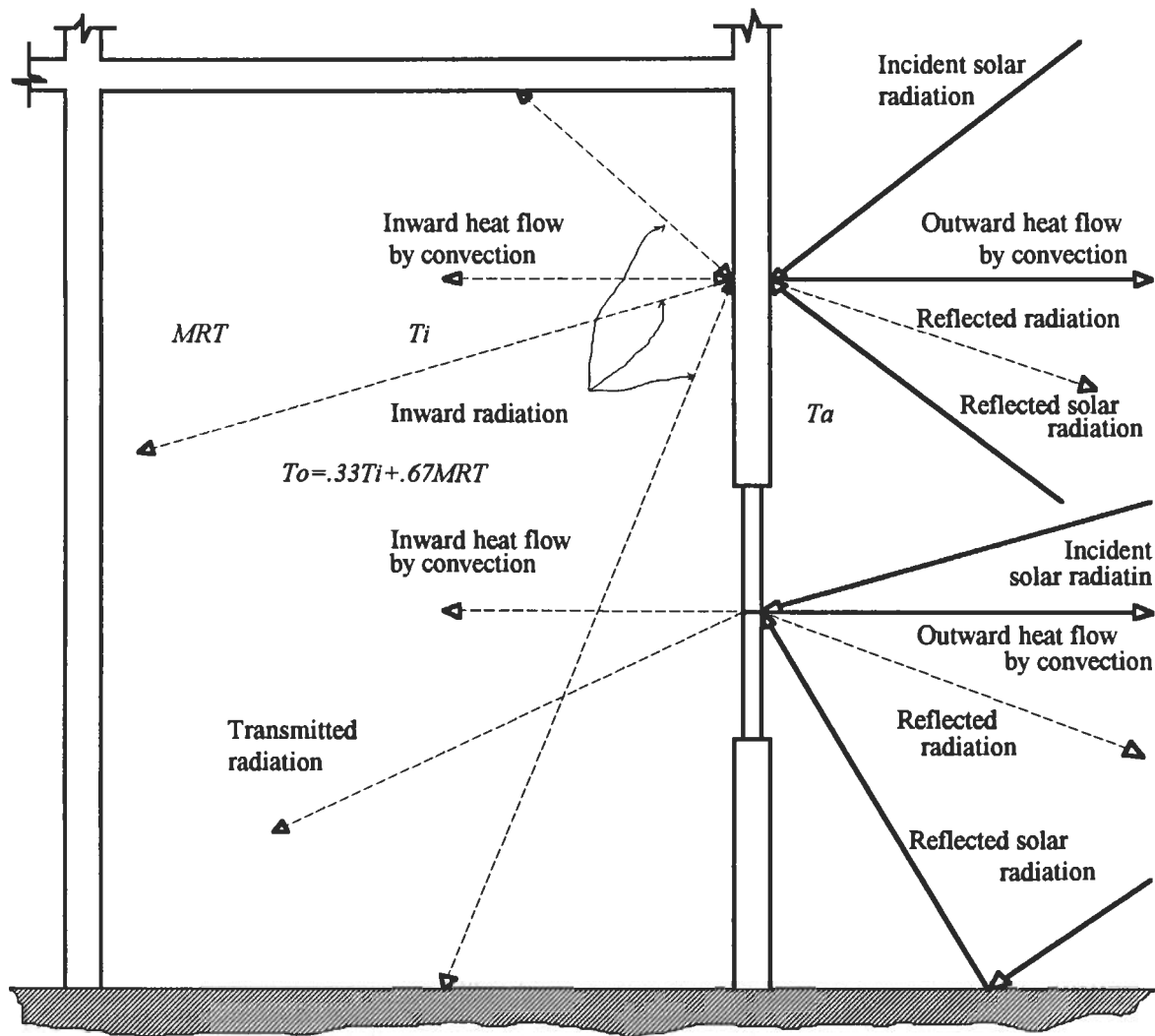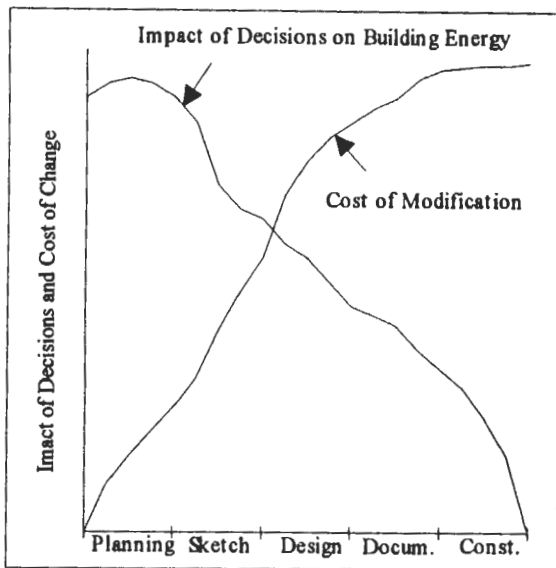
Figure 1 Heat transfer through the building envelope.

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Figure 2 Impact of decisions on building thermal performance and cost of modification.

Traditional practice has been followed in choosing the capital and operating cost as the criterion of optimization. Wilson and Templeman (20) 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 technique, they developed a computer model that gives 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 has 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 are also assumed to be known (20). These assumptions make their model of limited help in providing building designers with prescriptive information that are mostly needed in the early phases of the design process.

D'Cruz, Radford and Gero (4,5) developed an optimization model for early decision making of the design of parallelepiped 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 (19) 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 (15).

Based on thermal discomfort as the criterion of optimality, Gupta (10,11) 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 typical outdoor weather cycle for summer in Australian cities over several design variables.

SYSTEM FRAMEWORK

In order to make decisions using a systems approach it is necessary to understand processes and be able to control them. In order to understand processes, we need to identify their inputs and outputs and specify the associated properties with a proper relationship that links them together. Criteria are also necessary to compare output to objectives which help in controlling the process. Based on this, the basic framework of a systems approach to problems may be simplified as (12):

Input $\rightarrow$ Process $\rightarrow$ Output
$\rightarrow$ Process $\rightarrow$ Output

Given the complexity of contemporary buildings and the advancements in their technology, a systems approach can be applied to the building design process. A systems approach puts the problem in a more formal context, anchoring the critical elements

in relationships appropriate to the problem, arming the problem solver with an understanding of how to organize the parts of a problem and how to derive consistent solutions . In other words, it provides structure to ill-structured procedures. A systems approach is characterized by its attempts to arrive at decisions not only for the parts but for their total ordering as well through a logical and procedurally organized arrangement of steps (12).

THE BUILDING AS A THERMAL SYSTEM

Building design is a decision making process in which decisions are made on the shape, orientation and selection of the physical components of the building and their arrangements to achieve certain objectives. These decisions are usually limited by certain constraints some of which are outside the control of the designer. The framework of input, process and output approach is influenced by many factors in the building design process:

Inputs:
- Design know-how (professional and technical)
- Climatic conditions
- Energy sources

Objectives:
- Human needs
- Social needs
- Environmental objectives
- Technical objectives

Constraints:
- Cost
- Technology
- Human characteristics
- Physical environment
- Aesthetics
- Practicality
- Regulatory (codes, municipal req., ...etc.)

The inputs may come from the relation between the design subsystems (structural, mechanical, electrical,...etc.) or from outside the system as pre-specified values by the designer. Design constraints range from those imposed by the client to those related to municipal requirements as well as site restrictions - all of which have to be considered in the optimization process. The structure of the design process of an optimum building thermal design follows the basic framework of the systems approach as shown in Figure 3.

SYSTEM DESIGN VARIABLES

Proper integration of design variables that could affect thermal performance of buildings can help to minimize energy requirements to achieve comfort in an air-conditioned building as well as minimizing thermal discomfort in the occupied space in the absence of mechanical heating and air-conditioning systems. Design variables with significant impact on buildings' thermal performance vary over a range of design parameters including siting, building shape, glazing, wall and roof construction, massing, infiltration and operational parameters. Each parameter may be represented by one or more design variables. A summary of the important building thermal design variables considered in the optimization is shown in Table 1.

OBJECTIVE FUNCTION

The ultimate goal of building design is to provide occupants with a comfortable environment. In order to determine an optimum thermal design performance based on occupant comfort, it is necessary to establish a relationship between thermal comfort and the factors that have an impact on the thermal performance of buildings. The relationship can then be used to select an optimum combination of building design parameters that achieve the desired objectives. In order to control the design process in a systematic approach, it is necessary to formulate a criterion that can be used to compare the process outputs to objectives. Building thermal design can be optimized with the objective of minimizing building capital and operating cost, minimizing thermal load or minimizing thermal discomfort in the occupied space.

Cost optimization requires the distributing system and plant characteristics to be included as design variables. However, energy cost can fluctuate and might not be a good criterion to base the design decisions upon, especially in the early stages of the design process. Also, some important design parameters, such as building orientation can have significant thermal contribution while not costing anything. Therefore, for early decision making, an integral view of the building environmental performance based on criteria other than cost might be more desirable. Buildings thermal design is normally optimized to minimize energy requirements to achieve thermal comfort in the air-conditioned space. However, for unconditioned buildings minimum thermal discomfort can be the objective in the absence of environmental control systems.
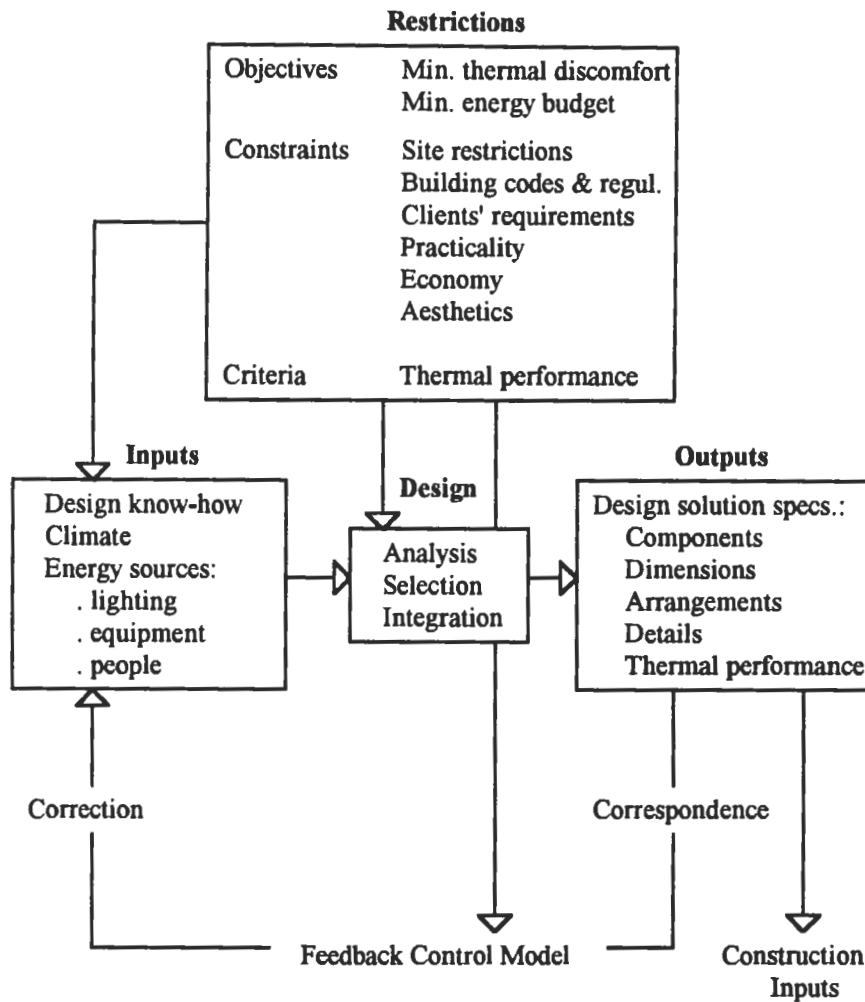
Figure 3 Structure of building thermal design optimization process.

For the purpose of the proposed model, two separate objective functions will be considered for both types of buildings. For the former case of air-conditioned buildings, especially those with high internal loads regardless of the outdoor environment, optimization based on the criterion of thermal discomfort might give unrealistic results when the operational parameters of the building are considered. Therefore, optimization based on the objective of minimum annual source energy utilization (MBtu/sq. ft.) will be considered. Such criterion can be used for any type or size of air-conditioned buildings which is already incorporated in the ENERCALC (6,7) energy simulation program that will be used in the proposed optimization model.

However, for the latter case unconditioned buildings, especially skin load dominated type, where interaction with the outdoor environment has a significant impact on their thermal performance, optimization based on the occupants thermal discomfort as the criterion of optimality, similar to that followed by Gupta (10), is found to be more desirable since an environment with minimum thermal discomfort conditions is expected to yield optimum thermal loads. Both objectives will be integrated into the optimization model as two separate options. For thermal comfort evaluation in unconditioned building, an environmental index needs to be used as discussed next.

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TABLE 1
Building Thermal Design Optimization Variables

Parameter	Variable	Comment
Siting	Latitude, deg.	Pre-specified
	Longitude, deg.	Pre-specified
	Elevation above sea level, ft.	Pre-specified
	Climatic conditions	Pre-specified
Building shape	Gross floor area, ft^2	Pre-specified
	Building height, ft	Pre-specified
	Aspect ratio	
Orientation	Relation to north, deg.	
Glazing	Glass area / wall area, %	
	Shading coefficient	
	U-Value, $Btu/hr\text{-}F\text{-}ft^2$	
	Emittance	
Wall construction	U-Value, $Btu/hr\text{-}F\text{-}ft^2$	
	Surface absorptance	
Roof construction	U-Value, $Btu/hr\text{-}F\text{-}ft^2$	
Massing	Time lag of the envelope mass, hr	
	Internal mass, lb/ft^2 of floor	
Infiltration	Air changes per hour, ach/hr	
Operational	Lighting, W/ft^2	
	Equipment, W/ft^2	Pre-specified
	People, Btu/person	
	Schedule of use	
	Function	

Thermal Comfort

There has been a great deal of research on human sensation and thermal comfort. As a result of such extensive research, six major factors of human thermal comfort response have been identified. These factors of dry-bulb temperature, mean radiant temperature, air velocity, relative humidity, activity level and clothing can be classified into two major groups:

- Personal or physical factors (clothing and metabolism), most of which are under human control.

- Measurable environmental factors which can be controlled-to a certain extent-by the building designer (air and surface temperatures, air motion and relative humidity).

In typical indoor clothing, most people perform light, primarily sedentary activity (1), and for the purpose of this research, acceptable thermal environment is based on the assumption of typical indoor conditions. Therefore, we are interested in those measurable environmental factors that can be controlled by the designer within which thermal

comfort can be achieved given such specified typical conditions of personal factors.

ANSI/ASHRAE Standard 55-1992 (1) specifies an acceptable relative humidity range of 30 and 60 percent, and at low activity levels the influence of humidity on the recommended ASHRAE summer and winter comfort zones is minor. Changes in humidity levels can be offset by changing space temperature where an increase of 10% in relative humidity can be offset by a decrease of only 0.5 F (0.3 C) in air temperature.

Temperature, on the other hand, is the most important environmental parameter with respect to thermal comfort. The use of an index temperature that accounts for both dry-bulb and mean radiant temperatures may be useful in evaluating thermal comfort in a space. Operative temperature is numerically a weighted average temperature that integrates the influence of both air and mean radiant temperatures based on their respective convective and radiative heat transfer coefficients and is expressed as:

$$T_o = \frac{h_c T_a + h_r T_r}{h_c + h_r} \qquad \text{Equation (1)}$$

or

$$T_o = a T_a + (1-a) T_r \qquad \text{Equation (2)}$$

where

T_o = operative temperature;

T_a = air temperature;

T_r = mean radiant temperature (MRT);

h_c = convective heat transfer coefficient;

h_r = radiative heat transfer coefficient;

$a \leq 1$.

This weighted average temperature is considered to be a sufficient criterion for thermal comfort evaluation for unconditioned buildings provided that air velocity and relative humidity are within acceptable limits given typical indoor clothing and light activity level. Based on this criterion of thermal comfort, the objective function has been selected to minimize the discomfort degree hours in the occupied space subject to constraints on the variables that are under the control of the designer and can be formulated as:

Objective Function:

$$Min \ DDHS = \sum_{i=1}^{n} [(T_{oi} - T_{cu})^+ + (T_{cl} - T_{oi})^+]$$

Equation (3)

where

n = number of hours of the year, 8760 hrs;

T_{oi} = calculated comfort operative temperature at the ith hour, °F;

T_{cu} = comfort operative temperature upper limit, °F;

T_{cl} = comfort operative temperature lower limit, °F;

DDH= discomfort degree hours;

+ = only positive values are summed.

The objective is to minimize the area between the curves and the boundaries of the comfort zone for the occupied space operative temperature profile (as illustrated in Figure 4) by proper integration of the previously discussed design variables through the use of a proper optimization technique.

CONSTRAINTS

The choice and range of variations of design variables are governed by many factors. These governing factors include site restrictions, building codes and municipal regulations, clients' requirements, practicality, economy and aesthetics. Any one or more of these variables could be limited within a certain range by the designer to meet any of the above requirements.
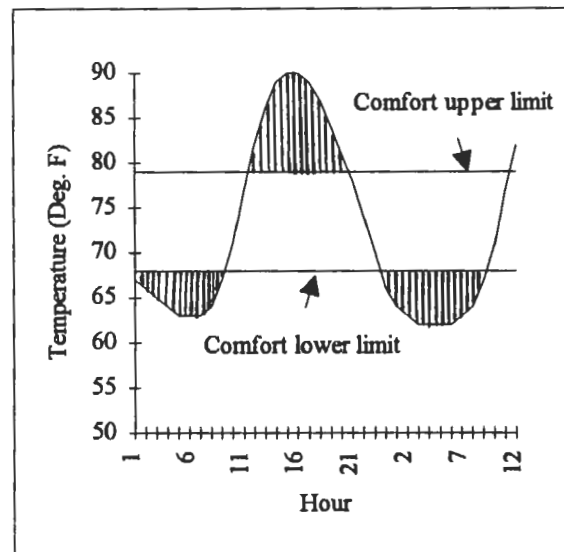
Figure 4 Temperature-time profile with omfort limits superimposed.

The designer is expected to have some knowledge about the building site, the building codes and local municipal regulations and client requirements from which certain constraints can be established on the variables for the control of the optimization. Such constraints include limits on the glazing area, dimensions of the building and thermal properties of its envelope components. For this model, controlling maximum and minimum values are specified in advance for each of the 15 design variables as follows:

$$U_{r\min} \leq U_r \leq U_{r\max}$$

$$U_{w\min} \leq U_w \leq U_{w\max}$$

$$a_{w\min} \leq a_w \leq a_{w\max}$$

$$TL_{\min} \leq TL \leq TL_{\max}$$

$$U_{g\min} \leq U_g \leq U_{g\max}$$

$$SC_{\min} \leq SC \leq SC_{\max}$$

$$e_{g\min} \leq e_g \leq e_{g\max}$$

$$P_{\min_i} \leq P_i \leq P_{\max_i}$$

$$ach_{\min} \leq ach \leq ach_{\max}$$

$$psf_{\min} \leq psf \leq psf_{\max}$$

$$1 \leq AR \leq AR_{\max}$$

$$0^o \leq orientation \leq 360^o$$

Where

U_r = roof thermal transmittance, Btu/hr F sq.ft;

U_w = wall thermal transmittance, Btu/hr.F.sq.ft;

α_w = wall absorptance;

TL = time lag,,hr;

U_g = glass thermal transmittance, Btu/hr.F.sq.ft;

SC = shading coefficient of the window;

ε_g = glass emittance;

P_i = percentage of glass area to wall area, Ag/Aw; i=1,..,4 for all four walls;

ach = air changes per hour, ach/hr;

psf = internal mass, lb/sq. ft. of floor;

AR = building aspect ratio, length of north wall/east wall.

OPTIMIZATION TECHNIQUE

In optimization, decisions are made on the best solution that satisfies specific objectives from among a range of feasible solutions. The application of

optimization techniques to architectural design is relatively new and requires careful formulation of the problem. The choice of a proper optimization technique is not easy for such ill-defined problems. Although there is a wide range of optimization techniques, not all of them are suitable for applications to building design problems. Many architectural problems require non-linear relationships with non-differentiable objective functions. Therefore, search methods of optimization, where the directions of minimization are determined from successive evaluations of the objective function, were found to be suitable for these types of problems. Examples of such methods include direct search of Hooke and Jeeves (14) and Flexible Polyhedron Search by Nelder and Mead (13,18).

Since the Flexible Polyhedron Search technique is more efficient and can deal with curving valleys and ridges, it will be implemented in the proposed model for the thermal optimization of building design. This method minimizes the objective function of n independent variables using $(n+1)$ vertices of a flexible polyhedron. The highest and lowest values of the objective function are then determined where the highest value is projected through the centroid of the remaining vertices and replaced by a better value. Then, the process continues and the polyhedron is adjusted systematically in the direction of improving objective values by the four operations of reflection, expansion, contraction and reduction until the search converges to the optimum.

The Nelder and Mead optimization technique is designed for unconstrained optimization type of problems. Therefore, provisions will be made to deal with the constraints imposed by the problem under consideration of the form $h_{\min_i} \leq x_i \leq h_{\max_i}$ as illustrated earlier.

THERMAL SIMULATION MODEL

Since the chosen objective functions can not be expressed directly in terms of building design variables, a thermal simulation model needs to be integrated with the optimization technique of Nelder and Mead for building thermal performance evaluation and comparison of successive values of the objective function. As discussed earlier, there are many powerful energy simulation programs available. However, in addition to its availability and access to the source code for modifications, the

ENERCALC program (6,7) was found to adequately represent the specified building thermal design parameters with accuracy while maintaining simplicity of simulation.

The program is suitable for evaluation of the two previously described objective functions. It calculates the annual source energy utilization for the building based on an hourly simulation. It also includes a space floating temperature option that gives hourly room temperatures. This will be utilized to calculate the mean radiant temperature (MRT) in the space for thermal comfort evaluation purposes.

The simulation program will then be used as a subroutine in the optimization model that is called whenever a new set of design variables are established to evaluate the objective functions of annual source energy utilization and annual Discomfort Degree Hours (DDH) at that point for comparison with previously performance tested results for air-conditioned and unconditioned buildings respectively.

CONCLUSIONS

A description of the basic framework of an optimization model for the thermal design of building envelopes has been presented. The model is intended to help building designers decide early enough in the design process on the best design solution that will satisfy the objective of minimum energy requirements to achieve thermal comfort in the occupied space. The model is based on transient heat transfer analysis for accurate representation of the building thermal behavior. Attempts were made to make the model simple and flexible for future additions of energy related issues not being considered at this stage such as daylighting. More development and validation of the model, as well as results from implementing the model into the design of buildings at different climatic regions will be presented in a near future.

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