Pergamon

Building and Environment, Vol. 32, No. 3, pp. 20

Printed in C
0360–1323/97 $

10375

PII: S0360–1323(96)00055–8

Optimum Thermal Design of Air-Conditioned Residential Buildings

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(*Received* 27 *March* 1996; *revised* 8 *June* 1996; *accepted* 26 *September* 1996)

Building design is a decision making process, in which decisions are made on the selection of certain design variables in order to achieve certain objectives (i.e. economy, thermal comfort, visual comfort, aesthetics, etc.). Information on the relationships between the variables and the desired objectives is necessary for proper decision making. Architects have traditionally reached their design decisions based on past experience. However, total reliance upon individual experience may lead to incomplete and inaccurate results. Therefore, given today's complexities in building design, as well as advances in computer technology, systematic approaches can be used as an aid to, not a replacement for, building designers in the decision making process.

This paper presents the results of implementing an optimization model to the design of energy conserving air-conditioned residential buildings in different climatic regions. Optimum sets of building design variables for typical U.S. and Saudi residences are presented, with the objective of minimizing annual energy consumption for those buildings. Optimization results showed that significant energy savings can be achieved by using optimization in the thermal design of buildings. Valuable design information on the selection and arrangement of various building components can be obtained in the early stages of the building design process by the implementation of optimization techniques, as in the model implemented in this paper. © 1997 *Elsevier Science Ltd.*

INTRODUCTION

WHOLE building energy design is a concept based on the idea that optimum energy performance is not a simple addition of parts, but rather a complex, dynamic integration of parts, a balancing of tradeoffs which turn negatives into positives [1]. Building design, especially for skin-load dominated buildings, is greatly influenced by the severity and variations of the climatic conditions for each region. This leads to the need for integrating the building thermal design with the overall design process, which would help the designer to decide early in the design process on some of the design alternatives that will minimize the energy needed to bring the space into comfort conditions.

Proper design of buildings can reduce the reliance upon supplemental mechanical heating and air-conditioning systems to achieve thermal comfort. The requirements for such systems depend on the function and schedule of the building, 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 architectural designers have little control. The climate, however, can only be modified by the designer through proper selection and integration of the building physical components throughout the design process. As a transition space, through which interaction between indoor and outdoor environment takes place, the building envelope is a determining factor in the consumption of energy in most buildings, and the selection of its components can significantly impact on the thermal performance.

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, as presented in a previous paper [2].

Coupling a proper optimization technique to the thermal performance analysis of buildings accounts for the interaction between different design variables and 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 climates.

This paper discusses the optimum thermal design of air-conditioned residential buildings at selected climates. This is the result of implementing the ENEROPT program, a direct search optimization model, in the design of these buildings [3].

THE OPTIMIZATION MODEL

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

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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 economics system using a systems approach three main elements are required:

- selection alternatives from which a selection is made (variables);
- accurate and quantitative knowledge of the system variables' interaction (constraints);
- a single measure of system effectiveness (objective function).

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.

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 [3].

For the thermal design of buildings, most of the efforts were directed to the development of simulation models [4]. However, the speed of today's computers and the availability of suitable energy simulation programs facilitates the integration of simulation models and optimization techniques to the thermal design of buildings for decision making purposes.

The model implemented in this study utilizes a direct search optimization technique coupled with an hourly simulation model to optimize as many as 14, mainly building envelope related, design variables subject to upper and lower constraints imposed by the designer with the objective of minimizing the annual energy consumption of air-conditioned buildings [3].

CLIMATIC REGIONS

Every site is unique, either in its governing constraints or in its microclimate and, therefore, it is impossible to describe all microclimates for any region in the world. However, available published weather data usually provide reasonable representations for regions with similar climate characteristics and can be modified to fit specific sites.

Subdividing regions into climatic zones is neither an easy nor a definite task. Climatic regions merge gradually into each other and no sharp line can ever be drawn to identify the boundary of one region from another. For a detailed energy analysis of a certain building, local weather data has to be used. However, for the purpose of early design decisions, information obtained from studies on typical buildings can be useful in studying thermal behavior at sites with similar climates.

A climate such as that of the United States can be subdivided into many climatic regions. Lechner [5], for example, described 17 regions while some others have described more or less climatic zones. Most sources agree with Olgyay [6] that there are four main climatic zones that represent, in general terms, the climate of the United States. For the purpose of this research, the climatic categorization by Olgyay will be used and four different U.S. cities and two Saudi Arabian cities will be used to represent the four common climate types of cool, temperate, hot–arid and hot–humid climates.

Cool climate

Madison, Wisconsin (43.13°N latitude, 89.33°W longitude, and 860 ft above sea level) was selected to represent this climate region. It is characterized by severe cold winter temperatures with short hot summers, which is of secondary concern for designers compared to the cold winters. Therefore, the sun is welcome during winter where it can be utilized to supplement heating during this cold period.

Temperate climate

Medford, Oregon (42.37°N latitude, 122.87°W longitude, and 1299 ft above sea level) was selected to represent this climate region of the northern California, Oregon and Washington coastal region. It is characterized by a very mild climate with cool winter temperatures and frequent rain with overcast skies. However, due to varying elevations and distance from the coast, large microclimate variations of this region are expected and should be considered by designers for specific projects [5].

Hot-arid climate

Phoenix, Arizona (33.43°N latitude, 112.02°W longitude, and 1112 ft above sea level) represents this climate of the Southwest desert of the U.S. It is characterized by extremely hot and dry summers with very large diurnal temperature ranges and moderately cold winters. Skies are clear most of the year and the main concern for a designer is summer overheating.

Hot-humid climate

Houston, Texas (29.9°N latitude, 98.37°W longitude, and 108 ft above sea level) represents this type of climate characterized by long hot and humid summers with very small diurnal temperature ranges. Winters, on the other hand, are short and mild which makes hot and humid summer conditions the main concern for building designers.

Two additional cities with available weather data representing the hot-arid and hot-humid parts of Saudi Arabia were also selected. Riyadh (24°N latitude, 46°E longitude, and 2000 ft above sea level) and Jeddah (21.3°N latitude, 39.1°E longitude, and 56 ft above sea level), Saudi Arabia have similar climates to those of Phoenix, Arizona and Houston, Texas, respectively, with some variations in the severity of the summer hot temperatures for Riyadh and the mildness of winters in Jeddah as well as variations in the latitudes and elevations above sea

Table 1. Outdoor comfort conditions for the six selected climates

City	% hours of the year			% discomfort degree-hours		Degree-days*	
	Comfort	Hot	Cold	Hot	Cold	Heating	Cooling
Phoenix, Arizona	20	39	41	47	53	1327	4200
Houston, Texas	29	25	46	21	79	1487	2569
Medford, Oregon	11	9	80	5	95	5110	761
Madison, Wisconsin	10	7	83	2	98	7609	642
Riyadh, Saudi Arabia	20	49	31	61	39	562	5075
Jeddah, Saudi Arabia	30	63	7	98	2	0	6365

*K-days = 5/9°F day.

level. Such variations allow investigation of their effect on the optimum thermal design of buildings. Also proper design guidelines for these localities can be drawn for designers' use in these parts of Saudi Arabia.

Comfort hours of the year, as well as discomfort degree hours, for each of these cities, based on a temperature comfort range of 68 to 79°F (20 to 26°C) of the outdoor dry-bulb temperature are summarized in Table 1. Annual heating and cooling degree days with reference to 65°F (18.3°C) base are also listed.

Those cities were selected to represent the subdivided climatic zones, in general terms, in order to address the main concerns and optimization trends for building designers at similar climates. The developed ENEROPT energy optimization model was used in the analysis, utilizing the hour-by-hour simulation capabilities of the ENERCALC program [3, 7].

RESIDENTIAL BUILDINGS

Residential buildings are characterized by being "skin-load" dominated with thermal behavior being significantly influenced by changes in the outside climate. Lighting and other internal loads are relatively insignificant to the thermal performance compared to commercial buildings. Pattern of use differs from one residence to another and typical energy analysis data, similar to that for office buildings, is not commonly available. However, most residences are occupied 24 hours, 7 days a week, and especially at night.

For the purpose of this research a typical 2400 ft^2 (223 m^2) residence was used for optimization. The characteristics of the analyzed building are as follows:

Building	Description
Location	Varies
Design temperature	Cooling 78°F (25.6°C) db; heating 73°F (22.8°C) db
Shape	Rectangular with 1.33 : 1 aspect ratio
Height	8 ft (2.4 m) floor-to-floor
Internal loads	0.9 W/ft^2 (0.084 W/m^2)
People	6 people
Hot water	20 gallons/person/day (75.7 l/person/day)
Zoning	Single zone
HVAC system	Heat pump system
Infiltration	Optimization variable
Orientation	Optimization variable
Fenestration parameters	Optimization variables
Envelope parameters	Optimization variables

IMPLEMENTATION

The ENEROPT optimization model was applied to the thermal optimization of the described buildings. Fourteen design variables were optimized for each air-conditioned building with the objective of minimizing the annual source energy utilization level (MBTU ft^{-2}). For the optimization purposes of this analysis, the same initial values of the optimized variables and the corresponding upper and lower boundaries of the limiting constraints used in all optimized buildings are shown in Table 2.

The average computer optimization run took 300 stages with about 700 hourly simulation runs to reach the optimum design solution based on a criterion of search termination of 0.0001 standard error of the values of the objective function. This corresponds to about 1 h on a 486–33 MHz IBM-PC. This speed of simulation is a feature of the simulation program which contributed greatly to the feasibility of conducting the optimization while maintaining hourly simulation.

The output from each optimization run consists of three parts. The first part includes building location information and a summary of the optimum thermal performance measures of the building, such as energy use as well as peak loads. The second part consists of a summary of the optimum building design, which is basically a list of the best optimum combination of the selected design variables along with the starting vector, as well as the

Table 2. Optimization variables' initial values and limiting constraints

Variable	Initial value	Lower bound	Upper bound
Wall U-value (BTU h^{-1} F^{-1} ft^{-2})	0.33	0.06	1.10
Absorptance	0.26	0.10	0.98
Time lag (h)	5.00	1.00	10.00
Roof U-value (BTU h^{-1} F^{-1} ft^{-2})	0.34	0.04	1.10
Glass U-value (BTU h^{-1} F^{-1} ft^{-2})	0.33	0.25	1.10
Shading coefficient	0.35	0.20	1.00
Emittance	0.36	0.20	0.98
% glass area N	20.00	15.00	99.00
E	20.00	15.00	99.00
S	20.00	15.00	99.00
W	20.00	15.00	99.00
Infiltration rate (ach h^{-1})	0.70	0.50	3.00
Internal mass (lb ft^{-2})	75.00	50.00	150.00
Orientation (° from south)	0	0	360

1 BTU h^{-1} F^{-1} ft^{-2} = 5.679 W m^{-2} C^{-1}; 1 lb ft^{-2} = 4.883 kg m^{-2}.

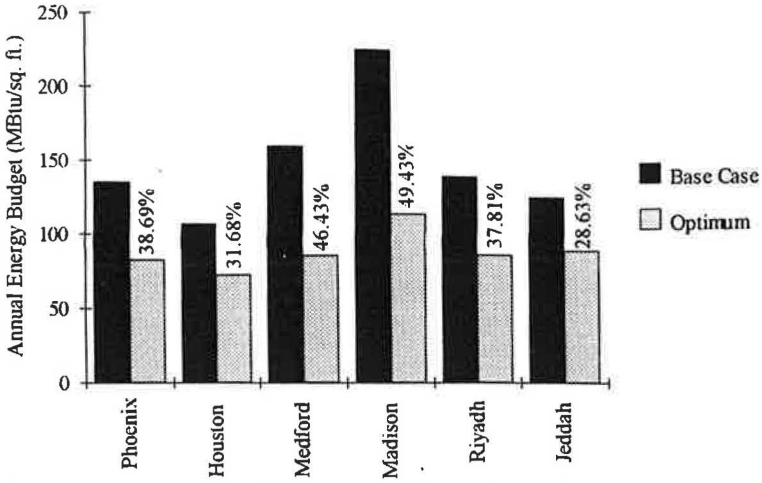

Fig. 1. Optimum annual source energy utilization in different climates for a typical two-story residence. $1\,\mathrm{BTU\,ft^{-2}} = 11.356\,\mathrm{kJ\,m^{-2}}$.

limiting constraints for each variable. The last part is a ranking of all the feasible solutions for the building from worst to best.

DISCUSSION OF THE RESULTS

Analysis of the optimization results for the described residential buildings in the six selected climates shows that the optimization model can provide designers with very useful information on the decision making process of building design. Results indicate that potential improvement of the thermal performance of buildings can be achieved from implementation of the model in the early phases of the design process.

Energy reduction evaluation

Being "skin-load" dominated, optimization results for residences showed significant thermal performance improvements with the optimized solutions for all climates as shown in Figs 1 and 2. It is for such buildings that early architectural design decisions may have more impact on thermal performance. Most variables with significance on the thermal performance of residences and similar envelope dominated buildings, are usually under the control of the designer during the preliminary phases of the design process and generalization of design guidelines is more applicable than for other types of buildings. Annual energy savings of up to 56% were achieved with optimization compared to the starting base case as shown in Figs 1 and 2.

Peak load evaluation

Optimization results produced significant reductions in residential heating and cooling peak loads. In Phoenix, for example, a reduction in peak cooling load from 69.93 to $35.3\,\mathrm{MBTU\,h^{-1}}$ was achieved in the optimized building, which corresponds to a 49.5% reduction with a corresponding reduction in the peak heating load of 52.2%. Optimization in other climates produced significant reductions as well. As a result, the air-conditioning system capacity can be reduced by as much as half in some situations, if buildings are properly designed. This has potential savings in energy consumption, energy demand, as well as savings in initial HVAC system costs due to the smaller equipment size needed. Peak heating- and

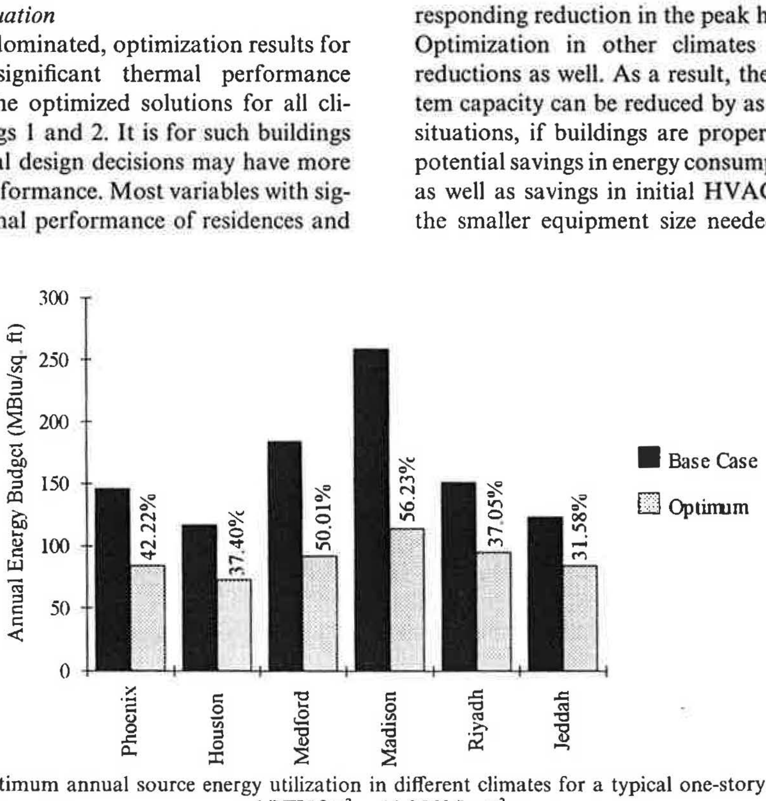

Fig. 2. Optimum annual source energy utilization in different climates for a typical one-story residence. $1\,\mathrm{BTU\,ft^{-2}} = 11.356\,\mathrm{kJ\,m^{-2}}$.

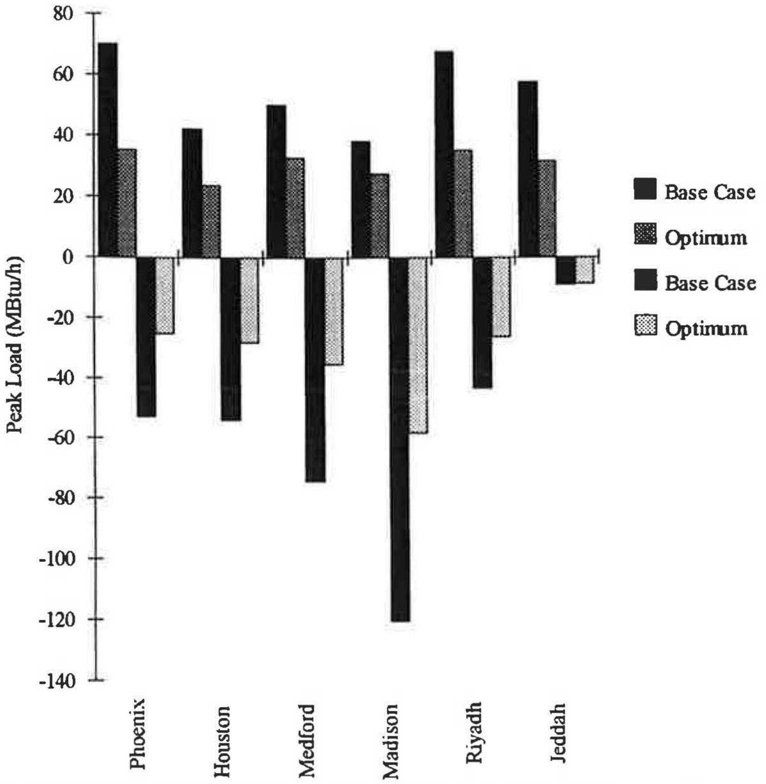

Fig. 3. Heating and cooling peak load evaluation for a two-story residence. 1 BTU ft^{-2} = 11.356 kJ m^{-2}.

cooling-load results, from the optimization of a two-story residence in the six selected climates, are shown in Fig. 3.

Optimization trends

Fourteen design variables were optimized for the one- and two-story residences with the general optimization trends as discussed below.

1. Orientation of the building with the long exposure facing south was found to be the optimum in all climates with a tendency for west of south orientation for cold and temperate climates. This was accompanied by trends to minimize north, east and west glass areas while calling for more glass areas for the southerly exposure to benefit from winter sun and minimize possible consequences of summer overheating. This was true for all climates and was more pronounced for cold and temperate regions.
2. Glazing optimization results revealed the need for minimum shading coefficients, especially in hot climates with the general tendency of minimizing glass areas for all exposures except the southerly exposure. Lower glass U-values were the trend of optimization for all climates. For the hot climate of Riyadh, Phoenix, Houston and Jeddah, minimum glass area on the east and west exposures was called for, with more flexibility for south and north exposures. For the cold climate of Madison, a larger glass area on the southerly exposure was called for with higher values for the shading coefficient to balance summer and winter energy tradeoffs. Optimization in the temperate climate of Medford, on the other hand, called for west of south orientation with more glass areas on the south-east exposure than other exposures.
3. Wall and roof construction optimization results revealed well insulated walls and roofs with the specified minimum U-values of 0.06 and 0.04 BTU h^{-1} F^{-1} ft^{-2}, respectively (0.34–0.227 W m^{-2} C^{-1}), regardless of climate. This is part of the solution in reducing conduction heat losses especially at night where cold hours and frequent occupancy of residences coincide. While a fixed roof absorptance value was used in the optimization, medium wall absorptance was the optimum in cold climates while lower values were called for in hot climates.
4. Infiltration optimum rates were to the lower end of the specified constraint boundary (0.5 ach h^{-1}) in all climates. However, due to frequent opening of doors and windows in residences, infiltration rates are expected to be generally higher than anticipated. Therefore, proper treatment of infiltration losses can contribute significantly in energy savings for such skin-load dominated buildings.
5. Massing of the building was optimized, based on the envelope time lag as well as the internal mass of the building. Although time lag of the building envelope did not show a strong trend, internal mass (lb ft^{-2} floor) was optimized at higher values for most buildings. This is where excess heat, whether from the sun or from the building internal loads, can be stored and released during unoccupied and cooler periods.
6. Building form optimization is thermally determined by the summer and winter thermal tradeoffs and the most critical season usually dominates the design optimization trend. Therefore, compact buildings are pref-

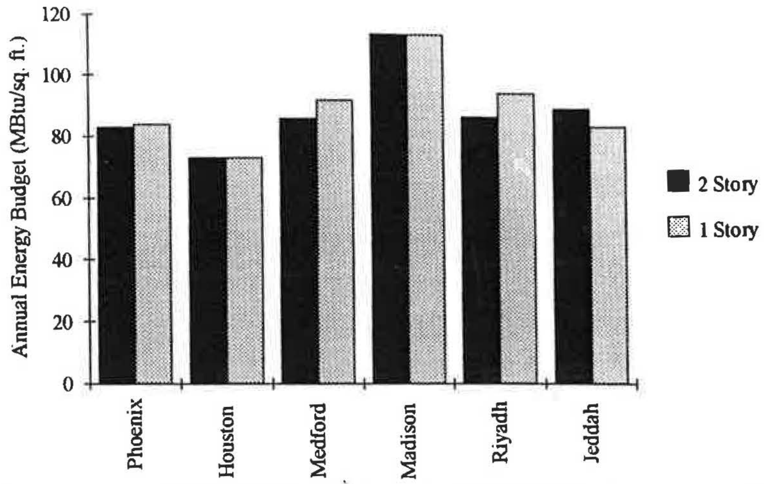

Fig. 4. Optimum annual source energy utilization levels in different climates for two shapes of residence. $1\ \mathrm{BTU\,ft^{-2}} = 11.356\ \mathrm{kJ\,m^{-2}}$.

erable during cold winter times, while less east and west exposures are generally desirable during hot summer times and their balanced benefits determine the optimum shape.

In order to investigate the impact of building form on thermal performance, the same residence was optimized as two- as well as one-story with the same gross floor area. The optimization results do not show significant differences in thermal performance of the two houses, however, suggesting that generally higher (two-story) buildings are thermally more desirable in hot-arid, temperate and cold climates as shown in Fig. 4. In addition to having more surface area-to-volume ratio, the one-story residence has more roof exposure for the same floor area which is generally less desirable in hot climates.

A summary of the optimum thermal design for a residence in the six tested climates is shown in Table 3. However, these are not unique design solutions and the interesting observation obtained from using optimization in building thermal design is in the interaction b the design variables that can not be achieved usir able by variable investigation of alternatives. The possible similar thermal performances could be ac with different combinations of design variables. important, as it indicates that for some designs t no unique optimum thermal design solution and di combinations of building elements and their ar ments, which might be different from traditional pr could reveal similar thermal performances as shc the four optimization results for a two-story reside Madison, Wisconsin of Table 4.

As a result, design priorities could shift from on ameter to another as some characteristics of tha ameter change. For example, the importance of the mal characteristics of the glass is proportional t optimum amount of glazing area and its distributior the building exposures, and vice versa, which also a to other building components as illustrated in Ta Therefore, the use of optimization in building d

Table 3. Optimum thermal design summary for an air-conditioned residence in different climates

	City					
Variable	Phoenix	Riyadh	Houston	Jeddah	Madison	Medf
Wall U-value ($\mathrm{BTU\,h^{-1}\,F^{-1}\,ft^{-2}}$)	0.09	0.06	0.11	0.06	0.06	0.0
Absorptance	0.30	0.24	0.55	0.17	0.42	0.3
Time lag	3.55	4.10	3.93	4.10	5.36	4.5
Roof U-value ($\mathrm{BTU\,h^{-1}\,F^{-1}\,ft^{-2}}$)	0.04	0.05	0.04	0.06	0.04	0.0
Glass U-value ($\mathrm{BTU\,h^{-1}\,F^{-1}\,ft^{-2}}$)	0.25	0.27	0.25	0.25	0.36	0.2
Shading coefficient	0.21	0.20	0.20	0.27	0.40	0.2
Emittance	0.20	0.39	0.20	0.34	0.36	0.2
% glass area N	15.32	17.46	22.98	15.17	16.60	17.4
E	15.00	15.67	17.75	15.00	15.00	43.6
S	15.00	15.22	21.40	15.00	21.64	15.3
W	18.91	15.61	17.13	16.34	15.24	28.4
Infiltration rate (ach)	0.51	0.50	0.50	0.54	0.50	0.5
Internal mass ($\mathrm{lb\,ft^{-2}}$)	140.86	62.98	82.41	137.57	77.53	109.5
Orientation	13	18	6	1	39	51
Opt. ($\mathrm{MBTU\,ft^{-2}}$)	83	87	73	90	114	86
Start. ($\mathrm{MBTU\,ft^{-2}}$)	135	140	107	126	226	160
% improvement	38.7	37.8	31.7	28.6	49.4	46.4

$1\ \mathrm{BTU\,ft^{-2}} = 11.356\ \mathrm{kJ\,m^{-2}}$; $1\ \mathrm{BTU\,h^{-1}\,F^{-1}\,ft^{-2}} = 5.679\ \mathrm{W\,m^{-2}\,C^{-1}}$; $1\ \mathrm{lb\,ft^{-2}} = 4.883\ \mathrm{kg\,m^{-2}}$.

Table 4. Alternative optimum thermal designs summary for an air-conditioned residence in Madison, Wisconsin

	Optimization run				
Variable	1	2	3	4	Centroid
Wall U-value	0.07	0.07	0.06	0.06	0.065
Absorptance	0.30	0.22	0.47	0.42	0.353
Time lag	2.94	1.00	1.08	5.36	2.60
Roof U-value	0.05	0.05	0.04	0.04	0.045
Glass U-value	0.26	0.25	0.30	0.36	0.293
Shading coefficient	0.46	0.48	0.41	0.40	0.438
Emittance	0.52	0.40	0.20	0.36	0.37
% glass area N	15.02	16.02	18.38	16.60	16.51
E	22.45	15.02	32.25	15.00	21.18
S	57.16	36.87	29.59	21.64	36.32
W	15.10	15.56	20.19	15.24	16.52
Infiltration rate	0.54	0.51	0.50	0.50	0.513
Internal mass	104.1	75.30	85.81	77.53	85.69
Orientation	1	13	8	38	15
Opt. (MBTU ft^{-2})	111.2	111.3	113.7	114.2	112.8
Start. (MBTU ft^{-2})	156	122	182	226	—
% improvement	28.8	8.5	37.4	49.4	—

1 BTU ft^{-2} = 11.356 kJ m^{-2}; 1 BTU h^{-1} F^{-1} ft^{-2} = 5.679 W m^{-2} C^{-1}; 1 lb ft^{-2} = 4.883 kg m^{-2}.

for specific projects is worthy for exploring new design possibilities, rather than reliance on trial and error investigation of different design alternative solutions.

CONCLUSIONS AND RECOMMENDATIONS

Optimization results showed that significant energy savings can be achieved by using optimization in the thermal design of buildings. Valuable design information, on the selection and arrangement of various building components, can be obtained in the early phases of the building design process by implementing the developed ENEROPT building thermal design optimization model. Such information could aid building designers in the decision making process, to achieve building design with optimum thermal performance.

The optimization results revealed not only lower energy use, but also lower peak heating and cooling loads. Therefore, operating, as well as initial, HVAC equipment costs can be reduced due to the smaller system capacity required to provide comfort for the optimized buildings. In addition, positive environmental impacts would also result from less reliance on artificial heating and air-conditioning systems.

Based on the optimization results of this research, a number of recommendations on the thermal design of buildings can be summarized as follows.

1. Careful consideration should be given to the amount and distribution of glazing over the exposures of the building, to balance summer and winter thermal trade-offs. The southerly exposure was found to be the most desirable glass exposure for all climates with varying amounts of optimum glass area in different climates. East and west exposures, however, are generally the least desirable glass exposures in all climates.
2. The glazing system shading coefficient is the first line of defense, especially in hot climates where glass shading treatment that would produce the lowest possible shading coefficient should be used.
3. Building orientation with the long side facing south is generally the optimum solution in all climates. Square buildings and north–south elongation are not thermally desirable, regardless of climate.
4. Wall colors with medium absorptance are preferable in cold and temperate climates, while low absorptance (light colors) is the optimum in hot climates.
5. Wall and roof insulation are recommended for buildings in all climates for more thermally comfortable space and, therefore, less energy requirements. Insulation helps in reducing conduction losses through the building envelope. Optimization results called for minimum U-values for both roof and walls. However, the roof U-value is generally more critical than that of walls and should be considered first.
6. Infiltration is the most difficult variable to measure and its losses are the most difficult to control. Therefore, based on the optimization results, the minimum infiltration rate should be allowed and careful treatment of cracks and leaks should be implemented. However, at climates where outdoor air could be utilized for cooling, especially on cool summer nights in hot–dry climates, controlled ventilation should be considered.
7. Due to frequent opening of doors and windows in residences, infiltration rates are expected to be generally higher than anticipated. Therefore, proper treatment of infiltration losses can contribute significantly in energy savings for such skin-load dominated buildings.
8. Proper treatment of building envelopes can significantly improve thermal performance especially for skin-load dominated buildings. Therefore, the use of optimization in the design of buildings and the selection of the envelope components is highly recommended.

Acknowledgement—The author would like to thank King Fahd University of Petroleum and Minerals in Dhahran, Saudi Arabia for their support throughout this research.

REFERENCES

1. Shaw, A., ed., *Energy Design for Architects*. Fairmont Press, GA, 1989.
2. Al-Homoud, M. S., Degelman, L. O. and Boyer, L. L., The framework of an optimization model for the thermal design of building envelopes. In *The Ninth Symposium on Improving Building Systems in Hot and Humid Climates*, Arlington, TX, 1994, pp. 100–109.
3. Al-Homoud, M. S., Design optimization of energy conserving building envelopes. Ph.D. dissertation, Texas A&M University, TX, 1994.
4. Lawrence Berkeley Laboratory, DOE-2 Users Guide. Berkeley, CA. Supported by the U.S. Department of Energy, 1979.
5. Lechner, N., *Heating, Cooling, Lighting: Design Methods for Architects*. John Wiley, New York, 1991.
6. Olgyay, V., *Design with Climate: Bioclimatic Approach to Architectural Regionalism*. Princeton University Press, Princeton, NJ, 1963.
7. Degelman, L. O., ENERCALC: a weather and building energy simulation model using fast hour-by-hour algorithms. In *The Fourth National Conference on Microcomputer Applications in Energy*, Tucson, AZ, 1991.