INTERACTION OF THE BUILDING ENVELOPE WITH HVAC SYSTEMS UTILIZING HEAT RECLAIM AND ECONOMIZERS

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ABSTRACT

The effects of building heating, ventilating, and air-conditioning (HVAC) system performance on the potential energy and cost savings with the combined use of heat reclaim and air economizer cycle operation were studied. Various combinations of heat reclaim and economizer cycle operation were simulated and evaluated in terms of annual energy savings and simple life-cycle costing for economizer and/or heat reclaim installation. An hourly building loads program (in C language) was developed that uses an effective temperature difference (ETD) method to calculate heating and cooling loads. To investigate HVAC system performance, the building loads program was then incorporated into system simulation programs for the following types of terminal systems: variable-air-volume (VAV) with reheat, four-pipe fan coil units, constant-volume dual-duct (or multizone), and single-zone reheat. For each of these, the primary system consisted of a heat reclaim chiller or heat pump with a double-bundle condenser, a supplementary heater, a heat rejection device (e.g., a cooling tower), and optionally, thermal storage. The capability to calculate hour-by-hour energy requirements for combined heat reclaim-economizer operation with priority to the operation of either heat reclaim or the economizer was then added. A simple method of life-cycle costing was then added, which enabled identification of the most economically viable heat reclaim-economizer ("best") combination. Results are presented to show the effect of internal load level, thermal mass, U-factor, and fenestration area.

INTRODUCTION

Energy conservation has been and continues to be of paramount importance to engineers and environmentalists alike. Concern for energy conservation in the area of building heating, ventilating, and air conditioning (HVAC) during the past few decades has led to the development and use of various types of heat recovery (reclaim) systems that recover building internal heat before it is discarded in the exhaust air or in the condenser water. The performance of heat recovery (reclaim) systems used in combination with an air economizer cycle was evaluated in this study.

Many commercial, institutional, and industrial buildings require simultaneous heating and cooling for prolonged periods during occupancy. This is especially true with buildings that have one or more core zones that must be cooled year-round. Frequently, therefore, the mechanical cooling and heating equipment must be operated jointly to provide the necessary comfort. This work studies the potential for savings in energy that can be realized by the use of HVAC systems that permit the transfer of heat from areas of heat surplus in the building to areas requiring heat. Such systems would be broadly classified as applied heat recovery or heat reclaim systems and would include applied heat pump systems.

Air economizer cycles have been widely used for many years in all-air and air-water types of HVAC systems as a means to reduce operating time for chilling equipment. In an air economizer cycle, when cool outside air is available to be mixed with building return air to provide cooler air to the cooling and dehumidifying coil and thus provide "free cooling," more (than the minimum ventilation requirement of) outside air is supplied and the outside air fraction is increased up to a maximum of 1 (or 100%). This is done with a variable-position outside air damper controlled by a mixed-air temperature sensor ahead of the cooling coil in combination with an outdoor air enthalpy sensor. This variable-position damper typically is used in conjunction with a fixed minimum outside air damper so that the required ventilation air can always be made available for the building.

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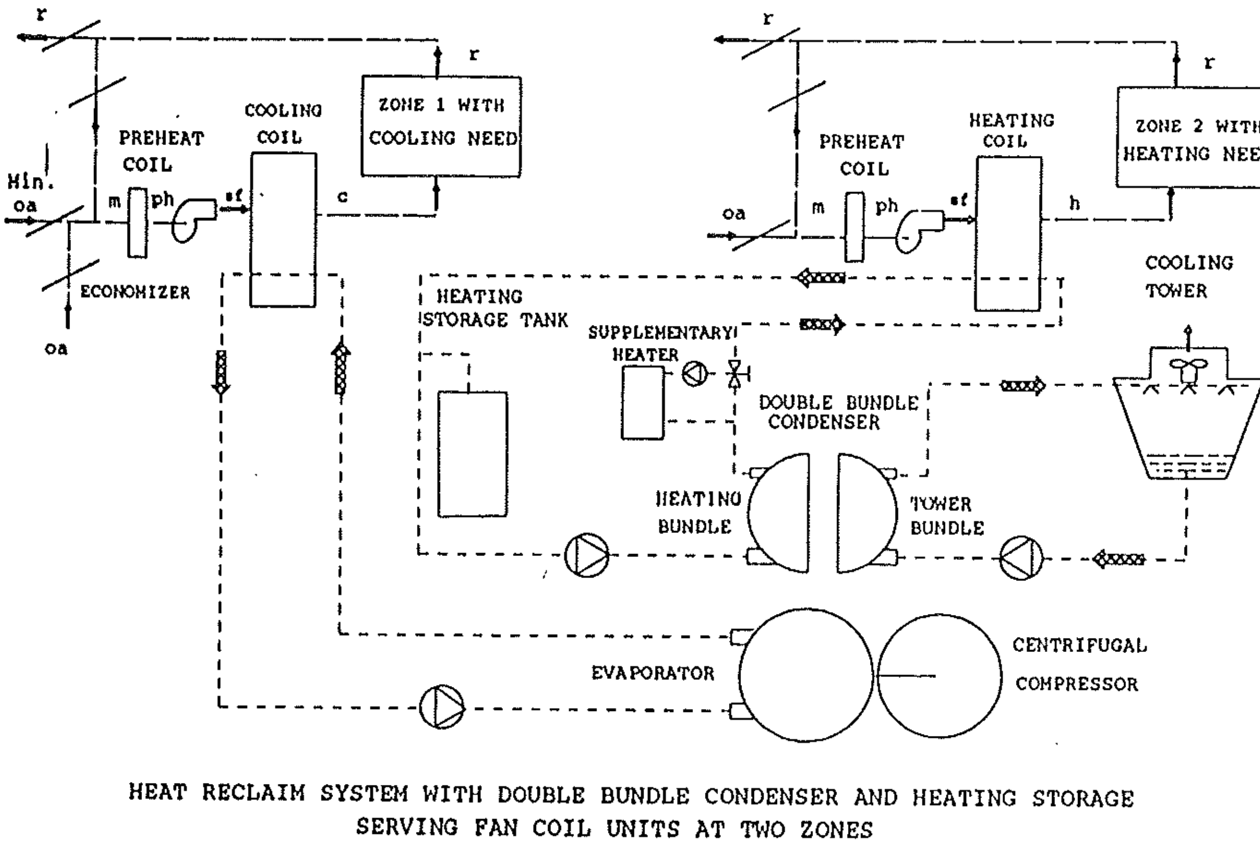

Figure 1 *Schematic of heat reclaim-economizer system.*

Some HVAC system designers have suggested that heat reclaim chillers and heat pumps should not be used in conjunction with an air-handling system that incorporates variable-position damper economizer control because the "free cooling" concept (of economizer operation) would result in higher annual operating costs than if only minimum outside air ventilation is used. Other investigators have found that outside air can be used economically in a heat recovery project if properly controlled to maintain an overall building "heat balance." Several have developed design guidelines for the use of an economizer with heat recovery. They concluded that accurately evaluated, time-related heating and cooling loads are an integral part of the design/selection process to select among an economizer system, a heat reclaim system, or a combination of both based on energy or cost considerations. They recommended that if an economizer is used in conjunction with a heat reclaim system, its control is critical and must be such as to provide for priority to heat reclaim. If such priority is not provided for, there might be heating cost penalties. The economizer operation should result in discarding only that heat that is in excess of what the building can use instantaneously for heating plus that later needed for heating and being placed in storage (if storage is available). The use of properly controlled and operated thermal storage consequently will make the use of an economizer less cost effective. Control of the economizer should not be based on the needs of individual building zones. They also concluded that if a heat reclaim system is to be used, cost considerations will favor the additional use of a properly controlled and operated economizer for high electrical energy rates.

A simple schematic of the combined heat reclaim-economizer system simulated in this study is presented in Figure 1. This is an internal-source, vapor-compression-type, four-pipe heat pump/chiller system using a centrifugal compressor and a double-bundle condenser. For purposes of illustration, the schematic shows only two zones (there could be any number in the actual system)—one calling for heating (maybe a perimeter zone) and the other calling for cooling (maybe an interior zone). The evaporator (water chiller) of the heat pump/chiller provides the cooling required, and the corresponding heat available at the double-bundle condenser can be used to heat water in the heating bundle (to provide heating for the other zone). If excess heat is available at the condenser (over and above the heating need for the particular hour), it could optionally be stored in a heating storage tank, and beyond the capacity of the storage tank, heat can be rejected at the cooling tower. If the heat available is insufficient to meet the heating requirements, additional heat can be provided by the supplementary heater.

The cooling required at the cooling coil depends on whether the economizer cycle is operating at that particular hour, which depends on either the temperature or the enthalpy of the outside air (based on the type of control sensor used). The system shown is always able to supply minimum outside air and can provide more outside air when called for by the economizer (i.e., when use of more outside air would result in "free cooling").

The opposing effects of economizer cycle and heat reclaim can be visualized from the schematic in Figure 1. If the control system employs the economizer cycle in zone 1, less cooling is required at the evaporator, but consequently less heat is available at the condenser for heating at zone 2 and the supplementary heater may have to be activated. It is evident that the control system is faced with the choice of whether to give priority to the economizer or to heat reclaim. This work studied the pros and cons of both priorities and examined the annual energy consumption in each case. It was found that the logic of the control system could result in large differences in the annual energy consumption and consequently in the payback period of the economizer and heat reclaim options.

While Figure 1 shows a terminal system employing fan coil units, the heat reclaim system easily could serve other terminal systems such as a variable-air-volume (VAV) (with reheat) system or a constant-volume dual-duct (or multizone) system.

As simulated, the VAV system with reheat has a central subsystem consisting of a cooling coil and dampers (for outside, exhaust, and recirculated air) and a preheat coil (optional). The central subsystem in this case also has economizer cycle capability and will always provide minimum (as per ventilation requirements) outside air. Centrally cooled air at, say, 55°F is available off the cooling coil. At each zone, the flow rate is controlled by the VAV boxes and reheated as per individual zone requirements. When this system is served by the double-bundle chiller/heat pump, the cooling needs would be met by the evaporator of the chiller/heat pump. Heat available at the condenser can be reclaimed (or recovered) and used for reheating needs (and preheating needs, if any).

The simulated constant-volume dual-duct (or multizone) system has central heating and cooling coils. Dampers (for outside, exhaust, and recirculated air) and a preheat coil (optional) make up the rest of the central subsystem. Further, economizer cycle capability is available in this case and minimum (as per ventilation requirements) outside air will always be provided. The dual-duct or multizone system is capable of excellent individual zone control, because hot and cold air are available and can be mixed to suit the needs of each zone. There is, of course, the penalty in energy of heating and cooling air supplied to the same zone. When this system is served by the double-bundle chiller/heat pump, the needs of the central cooling coil would be met by the evaporator of the chiller/heat pump. Heat available at the condenser can be reclaimed (or recovered) and used to provide hot water for the central heating coil (and preheating needs, if any).

METHODOLOGY

To determine the requirements of the building in terms of sensible cooling, sensible heating, dehumidification, and humidification for each hour, an energy balance was performed for each zone of the building on an hourly basis. It must be kept in mind that this analysis was aimed at developing a simplified, reasonably accurate procedure that would provide a common basis upon which different terminal and primary systems could be analyzed and the performance of those systems with the simultaneous operation of heat reclaim and economizer cycle could be studied.

The approach used in this study to calculate building cooling loads may be called an "effective temperature difference (ETD) method with time averaging (TA). The following relations were used to first compute the instantaneous heat gains and then time-average them to obtain the cooling loads.

1. *Instantaneous Heat Gains.* The components of sensible heat gain (heat losses were treated as negative gains) were
   - (a) transmission gain through exterior walls and roof,
   - (b) direct solar gain through windows,
   - (c) gain through windows other than direct solar gain (conductive gain),
   - (d) gain due to people in the zone, and
   - (e) gain due to internal loads in the zone (lights, computers, etc.).

The sensible transmission heat gain through each exterior wall or roof of a given zone, for the particular hour, q_{ext} in Btu/h, was given by

$$q_{ext} = U_{ext} \cdot A_{ext} \cdot \text{ETD} \tag{1}$$

where

U_{ext} = design overall coefficient of heat transfer (Btu/h·ft²·°F);
A_{ext} = area of this exterior wall or roof surface (ft²);
ETD = effective temperature difference (°F)
= $t_e - t_i$;
t_e = sol-air temperature (see chapter 26 of ASHRAE [1989]) (°F)
= $t_{oa} + (\alpha/h_o) \cdot I_t - (\varepsilon \cdot \delta R/h_o)$;
t_i = inside air temperature (°F);
t_{oa} = outside air temperature (°F);
α = absorptance of the surface for solar radiation;

h_o = coefficient of heat transfer by long-wave radiation and convection at the outer surface (Btu/h·ft^2·°F);

I_t = total normal intensity of solar radiation incident on the surface based on orientation, location, and hour of year (Btu/h·ft^2);

ε = hemispherical emittance of the surface;

δR = difference between the long-wave radiation incident on the surface from the sky and the surroundings and the radiation emitted by a black body at outside air temperature (Btu/h·ft^2)
(1) for the roof (horizontal surface), $\delta R \approx 20$ Btu/h·ft^2 and $\varepsilon\delta R/h_o \approx 7$°F (ASHRAE 1989);
(2) for an exterior wall (vertical surface), $\delta R = 0$ is assumed (ASHRAE 1989).

The sensible direct solar heat gain through each window (or glass exposure), q_{solar}, in Btu/h, was given by

$$q_{solar} = SC \cdot SHGF \cdot A_{glass} \quad (2)$$

where

SC = shading coefficient to account for interior and exterior shading;

SHGF = solar heat gain factor by orientation, location, and hour of year (Btu/h·ft^2); and

A_{glass} = area of window (ft^2).

The sensible conductive heat gain through each window of a given zone for the particular hour, $q_{conductive}$ (in Btu/h), was given by

$$q_{conductive} = U_{glass} \cdot A_{glass} \cdot (t_{oa} - t_i) \quad (3)$$

where

U_{glass} = design overall coefficient of heat transfer (Btu/h·ft^2·°F) and

A_{glass} = area of window (ft^2).

The sensible heat gain due to people in the zone, q_{people} (in Btu/h), was given by

$$q_{people} = N_{people} \cdot qsens_{person} \quad (4)$$

where

N_{people} = number of people in the zone

$qsens_{person}$ = sensible heat generated per person, Btu/h person.

The sensible heat gain due to internal loads in the zone (e.g., lights, business machines, computers, etc.), $q_{internal}$ (in Btu/h), was given by

$$q_{internal} = (W/ft^2) \cdot A_{floor} \cdot 3.413 \quad (5)$$

where

W/ft^2 = internal load density (W/ft^2) and

A_{floor} = floor area of the zone (ft^2).

The latent heat gain, q_{latent}, was only that due to people in the zone and was given, in Btu/h, by

$$q_{latent} = N_{people} \cdot qlat_{person} \quad (6)$$

where

$qlat_{person}$=latent heat gain per person, Btu/h person.

2. *Time-Averaging Scheme.* The cooling load of a conditioned space for a particular hour is the rate at which heat must be removed to maintain that space at a given temperature. The sum of all instantaneous heat gains of a conditioned space does not necessarily equal the cooling load for the space at that time. The origin of the difference between instantaneous heat gain for a conditioned space and the corresponding space-cooling load has been dealt with in chapter 26 of ASHRAE (1989). While a convective type of heat gain is felt by the space immediately (during the same hour) as a component of the cooling load, space heat gain by radiation is not immediate. Radiation must first be absorbed by the surfaces enclosing the space (e.g., walls, floor, and ceiling) and by the objects in the space (e.g., furniture and people). As soon as these surfaces and objects become warmer than space air, some of their heat is transferred to the air by convection. The composite heat storage capacity of these surfaces and objects determines the rate at which their respective temperatures increase for a given radiant input and thus governs the time delay (which could be a period of several hours) after which radiant components of instantaneous heat gain by the space are felt as space-cooling load. Commonly used building load calculation algorithms vary in the manner in which each of the space heat gains is accounted for, i.e., the percentage of each gain considered radiant and the number of hours over which that radiant part of the gain is felt by the zone.

   Each of the sensible heat gains that contributes to the building cooling load (as detailed in the previous section) has radiant and convective components, except the overall (outside air-to-inside air) gain through the glass, which does not have a radiant component. In this study, the space-cooling load was found by using the following time-averaging scheme.

   (a) Instantaneous value (value at the current hour) of conductive heat gain (gain other than direct solar) through windows as a component of cooling load for this hour was used.
   (b) Direct solar heat gain through windows, sensible heat gain due to people, and heat gain due to internal loads were each averaged over two hours (i.e., current hour and previous hour) to evaluate their contribution to the cooling load for this hour.
   (c) Transmission gain through exterior walls and roof were averaged over 2, 6, or 10 hours based on

whether the building thermal mass was light, medium, or heavy.

(d) By adding components of the cooling load from the first three elements, the hourly zone sensible cooling load was obtained.

Summing up values for all zones of the building that had a positive value (i.e., net heat gain for the zone for that hour) resulted in the hourly sensible cooling load for the building ($Q_{bldg\text{-}cool}$). Similarly, summing up values for all zones of the building that had a negative value (net sensible loss for the zone for that hour) resulted in the hourly sensible heating load for the building ($Q_{bldg\text{-}heat}$).

Unlike some sensible heat gains, latent heat gains are felt instantaneously; thus, summing up the latent gain for all zones in the building gave the hourly dehumidification need for the building ($Q_{bldg\text{-}lat}$).

All the calculations were performed by a program written in C language to run on a personal computer.

The input data provided to the loads program were in the form of two files, one containing data pertaining to the physical description and internal loads of the building and the other containing hourly weather data.

3. *Description of Test Building and the Base Case.* Figure 2 shows the test building that was simulated in this study. This building was modeled after an existing two-story, all-electric office building in St. Louis, Mo. The building was divided into 16 zones. Physical description and building operation (base-case) data were as given below.

Building roof area:	22,810 ft^2
Building floor area:	45,620 ft^2
Building exterior wall area:	9,460 ft^2
Building glass area:	7,536 ft^2 (44% of exterior wall area)

The program has the capability to calculate building loads for any number of zones. The program can account for exterior walls facing any two directions (designated direction 1 and direction 2) and glass areas in each of those walls in each zone of the building. The directions that these walls face could be north, east, south, or west, which were denoted 0, 1, 2, and 3, respectively, for input to the program. The roof (horizontal surface) was treated as direction 4.

Data specified for each zone were the following:

- roof area,
- floor area,

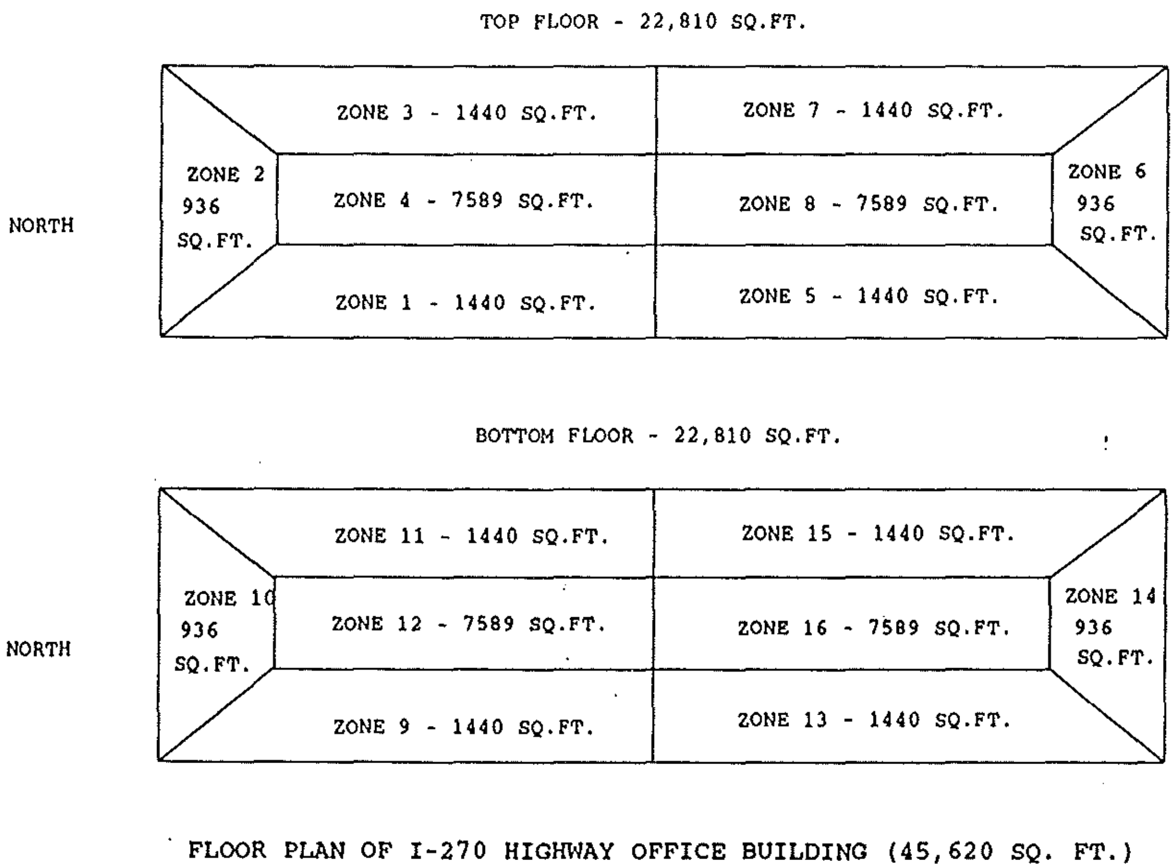

Figure 2 *Floor plan of simulated building (45,620 ft^2).*

- wall area facing direction 1,
- wall area facing direction 2,
- glass area facing direction 1,
- glass area facing direction 2,
- direction 1 (0, 1, 2, 3, or 4 for N, E, S, W or horizontal),
- direction 2 (0, 1, 2, 3, or 4 for N, E, S, W or horizontal),
- number of people during the day,
- internal load (W/ft^2) during the day,
- zone ceiling height,
- U-factor for the roof,
- U-factor for walls, and
- U-factor for glass surfaces.

4. *Weather Data Specifications.* The weather data used for the programs made as part of this study came from U.S. Weather Bureau hourly data (TRY format). The original data contained dry-bulb temperature, relative humidity, and cloud cover for every hour of the year (8,760 hours). Subbarao (1990) has covered the calculation logic by which the total normal intensities and solar heat gain factors for each orientation (north, south, east, west, and horizontal) can be calculated.
5. *Simulation Subroutines.* Although the procedures for estimating energy requirements used by detailed simulation methods vary considerably in their degree of sophistication, they all have three elements in common. These are the calculation of building (or conditioned space) loads, secondary equipment loads, and primary equipment energy requirements. Building (or conditioned space) load calculations are the first step and determine the amounts of energy that must be added to or extracted from the building to maintain thermal comfort. The second step translates the building loads into loads on the secondary equipment, which distributes the heating, cooling, and/or ventilating medium to the conditioned spaces. This step must include the calculation of all forms of energy required by the secondary equipment (i.e., electrical energy required to operate the fans and/or pumps), as well as energy in the form of heated or chilled water. The third step calculates the fuel and energy required by the primary equipment (which converts that fuel or electric energy to heating and/or cooling effect). It considers equipment efficiencies and usually part-load characteristics.

Using local weather data and user-input data for the building (containing a physical description and internal loads information), the building loads subprogram computes building requirements of sensible cooling, sensible heating, dehumidification, and humidification for any given hour.

The terminal systems subprogram uses building sensible cooling and heating information to calculate terminal system cooling, preheating, heating, and/or reheating as well as fan needs for the same hour. The terminal systems subprogram uses data input by the user (through a systems data file) to obtain relevant system parameters, such as minimum outside air requirements and cooling and heating coil setpoint temperatures, and performs complete air-side simulation.

The primary systems subprogram computes energy requirements at the chiller and supplementary heater to meet terminal system needs. It also computes the quantity of heat that must be rejected at the cooling tower or closed-circuit fluid cooler. User-input data for primary systems is obtained from the systems data file. For the cases with heating storage, values of heat stored also are computed by this subprogram.

To evaluate the energy-saving potential of heat reclaim and economizer cycle operation for different HVAC systems, five cases of heat reclaim and/or economizer operation for each HVAC system were considered. In each case, minimum outside air was provided when the economizer was not in operation. These cases were as follows:

Case 1: System operation with neither heat reclaim nor economizer operation, which was considered to be the base case.

Case 2: System operation with only economizer operation (and no heat reclaim at all).

Case 3: System operation with only heat reclaim (and no economizer operation at all).

Case 4: System operation with both economizer and heat reclaim operation, but with priority given to economizer operation.

Case 5: System operation with both economizer and heat reclaim operation, but with priority given to heat reclaim operation.

Cases 1, 2, and 3 were simulated to get an idea of the extreme situations in these combined heat reclaim-economizer systems. Cases 4 and 5 were simulated to study the effects of assigning priority to economizer cycle operation and to heat reclaim operation, respectively.

A sizing subprogram was added as a front end to each system simulation program to first size equipment. Following the sizing, annual energy requirements were estimated for each of the five cases of heat reclaim and/or economizer operation outlined. These energy calculations were then used in an economic analysis to establish the cost-effectiveness of the conservation measures studied, namely, heat reclaim and/or economizer operation. This study considered a simple payback method of economic analysis, which considered installed costs for heat reclaim and economizer system additions/modifications to the HVAC system and computed the payback periods for each of these options.

PARAMETRIC STUDY AND DISCUSSION OF RESULTS

One of the main goals of this study was to identify the heat reclaim-economizer combination that would result in the least consumption of annual total HVAC energy for various building configurations and HVAC system types and operating conditions. Effects studied in this work include

- influence of building location,
- influence of building U-factors and thermal mass,
- effects of internal load,
- influence of amount of fenestration area, and
- effect of number of hours of system operation.

To begin the parametric study, an initial set of runs of the system simulation programs was made for the test building located in St. Louis. Heat storage capacity was set to zero (i.e., not available) for this set of runs. Also, internal load density was set at 2.9 W/ft^2 in every zone of the building. The HVAC system was operated for 12 hours (from 7 a.m. to 7 p.m.) in every 24-hour period. The floor area of the test building was 45,620 ft^2. Following the set of runs for St. Louis, the location of the building was "moved" (in the sense of simulation) to Minneapolis, Minn., Houston, Texas, and Phoenix, Ariz., and the resulting changes for each terminal system were observed. Based on life-cycle costing that used simple payback calculations, the most economically viable heat reclaim-economizer combination was identified from the five cases. Computation of the annual total HVAC energy for almost all the situations considered in the parametric study showed that case 4, operation with both economizer cycle and heat reclaim but with economizer priority, resulted in greater total HVAC energy than case 5, operation with both but with heat reclaim priority. This translated into greater operating costs (based on a fixed unit cost of energy, $0.08/kWh in this study) for case 4 in comparison to case 5; therefore, case 5 would be the better choice in such situations. For the few situations in which case 4 resulted in less total HVAC energy use than case 5, the additional savings due to heat reclaim after operation of the economizer cycle were so small that a choice of case 4 over case 2, operation of only the economizer cycle, could not be justified.

Using the VAV with reheat system (test building at St. Louis), estimates for annual cooling (i.e., annual electrical energy to run the chiller), annual heating (i.e, annual electrical energy for the supplementary heater, and annual total HVAC (i.e., sum of annual cooling, annual heating, and annual fan energy) were computed to be as shown in Table 1. Annual fan energy for this system was estimated as 136,000 kWh. It is evident from the table that the case of heat reclaim priority is predicted to need the least annual total HVAC energy. The annual

TABLE 1 Annual Energy Estimates Using the VAV with Reheat System (St. Louis)

Case	Annual Cooling (kWh)	Annual Heating (kWh)	Annual Total HVAC (kWh)
Base case:	543778	533778	1213204
With only economizer:	344037	533778	1013464
With only heat reclaim:	543777	23819	703245
Economizer priority:	344037	434263	913949
Heat reclaim priority:	461311	23846	620806

TABLE 2 Savings in Annual Energy Using the VAV with Reheat System (St. Louis)

Case	Cooling Saved (kWh)	Heating Saved (kWh)	Total HVAC Saved (kWh)
With only economizer:	199740	0	199740
With only heat reclaim:	0	509959	509959
Economizer priority:	199740	99516	299256
Heat reclaim priority:	82466	509932	592398

TABLE 3 Percent Savings in Annual Energy Using the VAV with Reheat System (St. Louis)

Case	Cooling Saved (%)	Heating Saved (%)	Total HVAC Saved (%)
With only economizer:	36.7	0.0	16.5
With only heat reclaim:	0.0	95.5	42.0
Economizer priority:	36.7	18.6	24.7
Heat reclaim priority:	15.2	95.5	48.8

energy estimates of Table 1 show combined operation of economizer cycle and heat reclaim resulted in less annual total HVAC energy use than the cases in which only the economizer or only heat reclaim was used. Further, it may be noted that heat reclaim priority operation was estimated to result in less total HVAC energy use than economizer-priority operation.

To see the effects of economizer and heat reclaim operation individually and in combination more clearly, savings for each of cases 2 through 5 with respect to the base case or case 1 are shown in Table 2, and percent savings are shown in Table 3. Economizer operation reduced the cooling energy estimated, but did not affect supplementary heating, as expected. Only heat reclaim (with no economizer operation) resulted in a saving in estimated heating energy but no saving in energy required for cooling, again as was to be expected.

A simple economic analysis also was done in this study after computations for each of the five heat reclaim-economizer combinations had been completed. Assuming that the cost of energy was $0.08/kWh, base-case energy costs were as follows.

Annual cooling energy cost = $43,502 (0.95 $/ft^2)
Annual heating energy cost = $42,702 (0.94 $/ft^2)
Annual total energy cost = $97,056 (2.13 $/ft^2).

TABLE 4 **Cost Savings Using the VAV with Reheat System (St. Louis)**

Case	Cost Savings (%)	$\$/ft^2$ Savings
With only economizer:	16.5	0.35
With only heat reclaim:	42.0	0.89
Economizer priority:	6.8	0.14
Heat reclaim priority:	48.8	1.04

Cost savings with respect to case 1, the base case (which had neither heat reclaim nor economizer operation), are shown in Table 4. Cost savings were computed as savings percent of base-case costs and also as savings per ft^2 of building floor area.

A desired payback period of 3.0 years was assumed. The payback periods of heat reclaim only, heat reclaim priority over economizer, and economizer priority over heat reclaim were all less than three years. For the VAV with reheat system for the test building in St. Louis, however, the operation of *both economizer and heat reclaim with heat reclaim priority,* case 5, was the "best" case producing the greatest savings.

A comparison of potential savings that may be realized using each of the four types of terminal systems investigated with the "best" case (heat reclaim priority with economizer) for the test building located at St. Louis is presented in Figure 3. It may be recalled that when the terminal system chosen was either of three systems, namely, VAV with reheat, multizone (or dual-duct), or single-zone reheat, the "best" case was found to be case 5, operation of the combined system with heat reclaim priority. But when the four-pipe fan coil system was chosen, the "best" case was identified as case 2, only economizer operation.

Heating savings of 98% to 100% demonstrated clearly that combined operation with heat reclaim priority successfully compensated for heating needs using reclaimed heat. The savings in total HVAC energy were truly remarkable—ranging from 45% for the multizone or dual-duct system up to 60% for the single-zone reheat system. Savings of $\$1.04/ft^2$ for the VAV with reheat correspond to \$47,445 saved annually (for the 45,620-ft^2 test building).

Effects of Internal Load

With the increasing influx of computers and business machines (for printing, copying, calculating, etc.), the internal load in the conditioned space is a parameter that varies greatly at design time in today's air-conditioned commercial, industrial, or institutional building. To see what effects internal load density had on annual

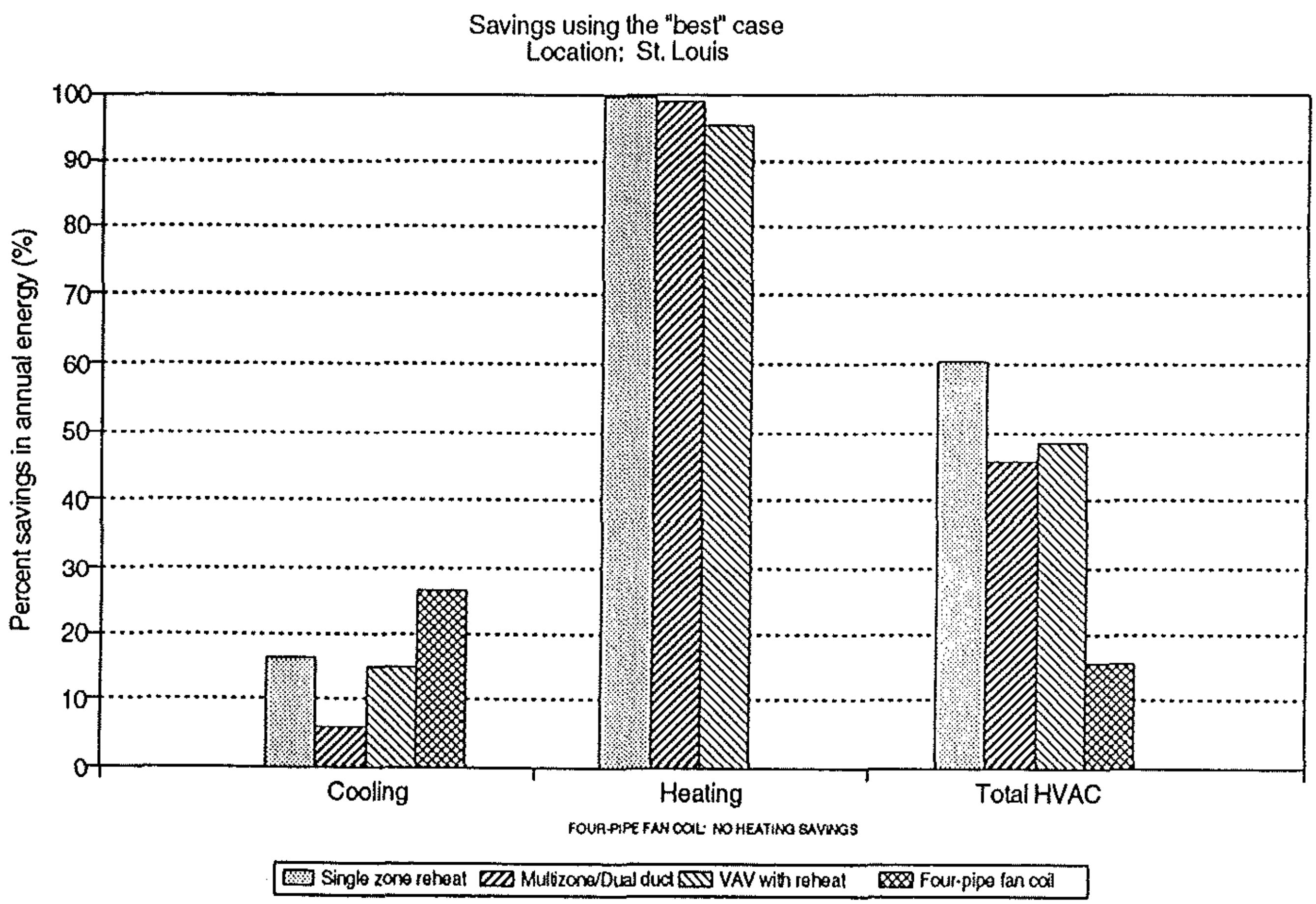

Figure 3 *Percent savings using the "best" case for different types of HVAC systems.*

cooling, heating, total HVAC energy, and on the payback periods for different combined heat reclaim-economizer systems, runs were made using the VAV with reheat system for the test building in St. Louis without and with the capability of heat storage, at internal load densities of 2.9, 6, 9, and 12 W/ft^2.

Percent savings in annual cooling energy, heating energy, and total HVAC energy are shown in Table 5. Savings in annual total HVAC cost in \$/ft^2 and payback periods also are presented. Since case 5, combined operation with heat reclaim priority, was used, as internal load density increased it was observed that annual HVAC cost savings (\$/ft^2) increased and the payback period decreased. This was expected because as the internal load increases, more heat is available for reclaim and thus can be used to meet the heating needs. Once heating needs are completely accounted for, the economizer cycle is able to provide more savings in cooling.

TABLE 5 **Effect of Internal Load Density (W/ft^2) on Savings and Payback Results Using the "Best" Case for the VAV with Reheat System (St. Louis)**

Without Heat Storage	2.9 W/ft^2	6 W/ft^2	9 W/ft^2	12 W/ft^2
Annual cooling energy saved (%)	15.2	25.7	31.9	35.7
Annual heating energy saved (%)	95.5	99.9	100	100
Annual total HVAC energy saved (%)	48.8	44.5	40.8	38.7
Annual total HVAC cost saved (\$/ft^2)	1.04	1.06	1.10	1.20
Payback period of "best" case (years)	0.46	0.45	0.43	0.40

Effect of Thermal Mass

Figure 4 shows graphically the influence of the building thermal mass for a building using the VAV with reheat system incorporating both heat reclaim and economizer operation under optimum conditions. The results are presented as the reduction in energy cost when moving from light construction to medium construction to heavy construction. Results are location dependent, as illustrated in the figure. Maximum savings of \$0.05/ft^2 are obtained when moving from light to heavy construction for the Houston climate.

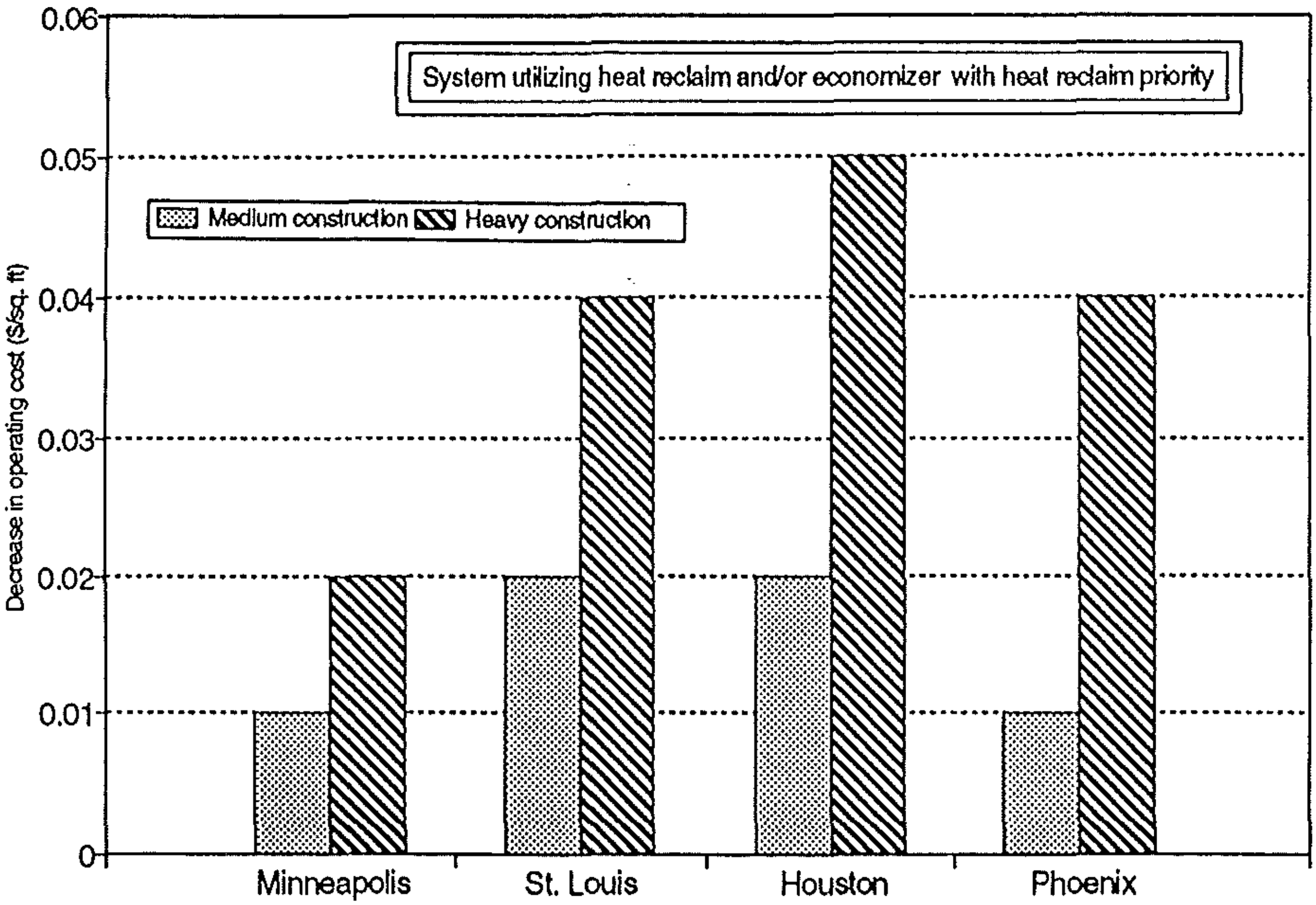

Figure 4 *Operating cost variation with thermal mass of building envelope (VAV with reheat system incorporating optimum combined heat reclaim/economizer operation).*

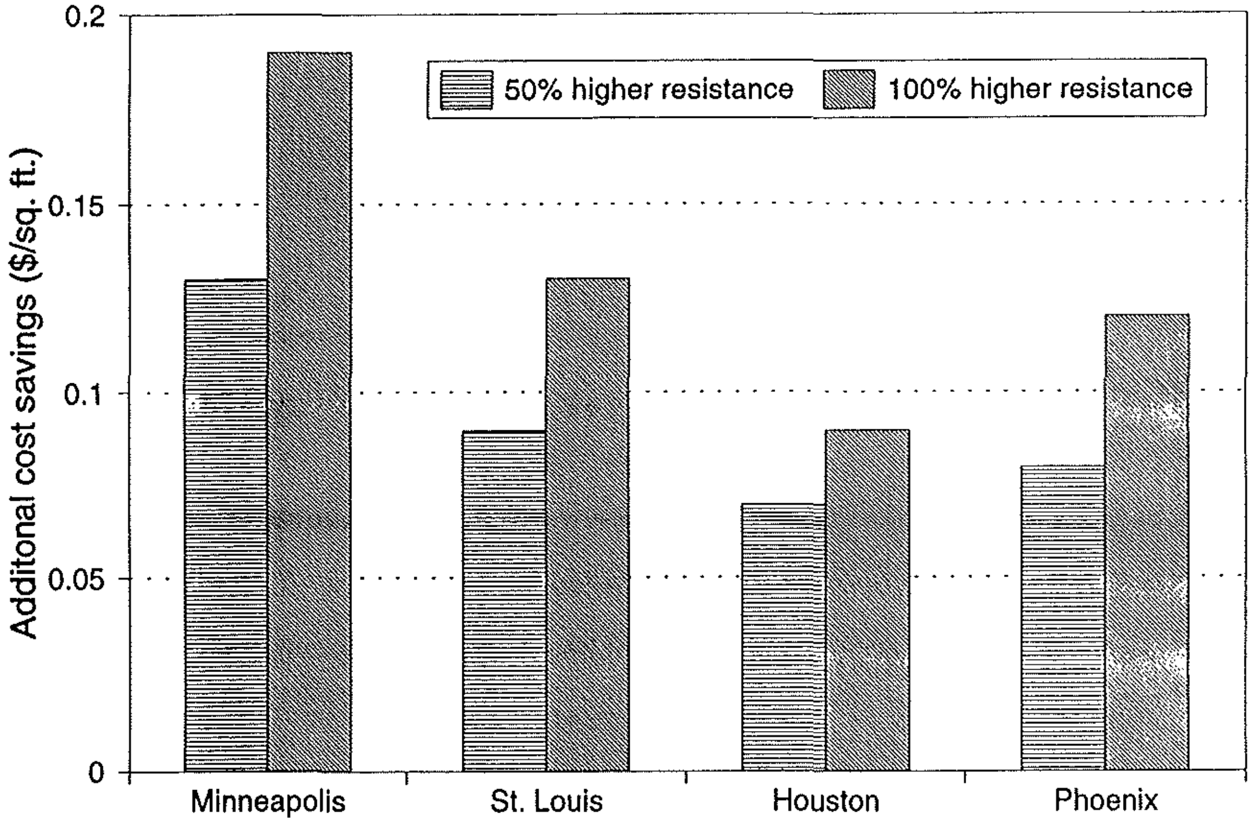

Figure 5 *Energy cost savings with increased thermal resistance (VAV with reheat system incorporating optimum combined heat reclaim/economizer operation).*

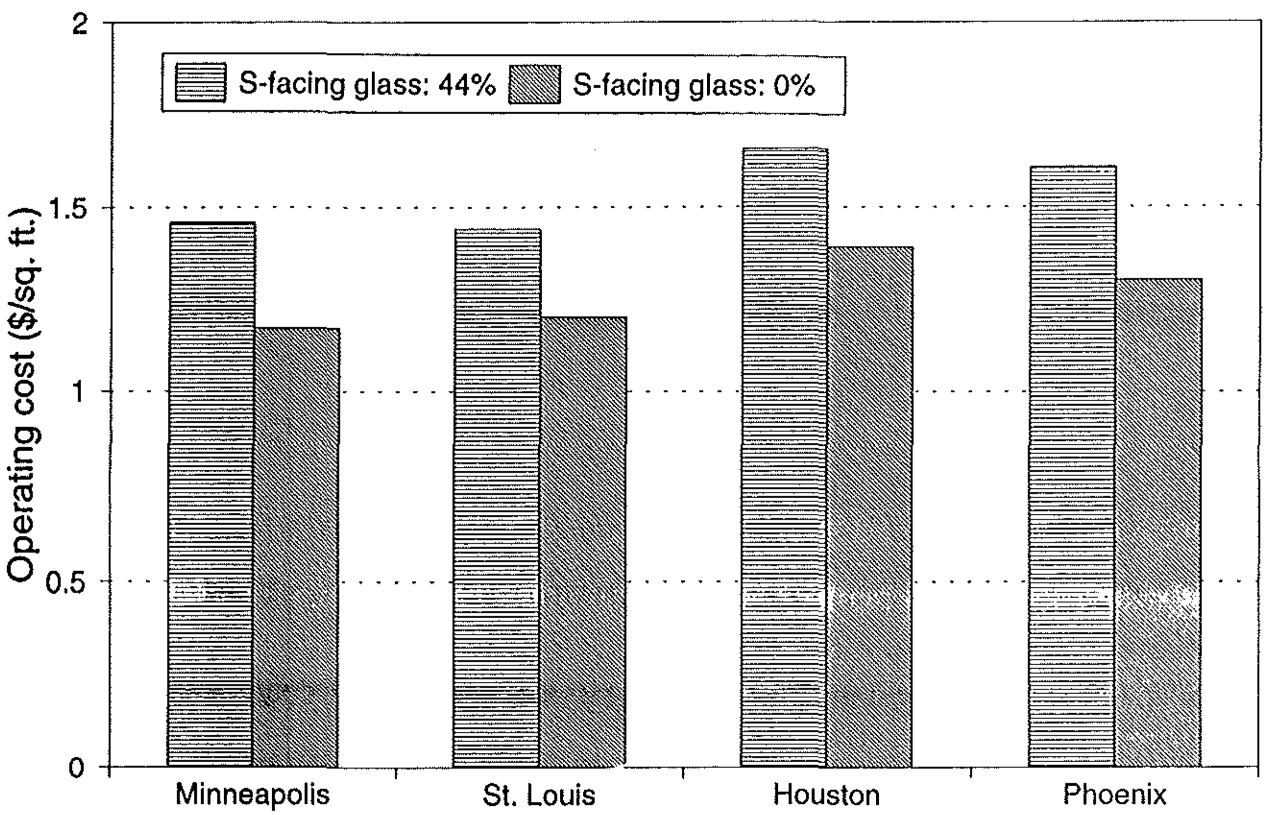

Figure 6 *Operating cost for different fenestration areas (Multizone system incorporating optimum combined heat reclaim/economizer operation).*

Effect of Wall and Roof U-Factors

Figure 5 illustrates the effect of various levels of thermal resistance of wall and roof constructions on the operating cost for an HVAC system using the "best-case" control of combined heat reclaim/economizer operation. As was certainly expected, increasing the thermal resistance (decreasing the U-factors) of the walls and roof resulted in decreased energy cost. Maximum savings were found to occur for the cold climate of Minneapolis. Somewhat surprising was the greater savings to be realized in the more moderate climate of the Midwest (St. Louis) over that for the hotter climates. However, a closer examination shows that the winter savings for the cooler St. Louis climate are greater than the savings in summer for the other locations.

Effect of Fenestration Amount

The effect of the quantity of south-facing glass on the energy cost for a multizone-type HVAC system with both heat reclaim and economizer systems is shown in Figure 6. The results presented compare the operating (energy) costs for the two cases of the south-facing wall containing 0% and 44% glass. The glass was taken to be double-strength, single-pane. For all four locations, the energy costs decreased as the amount of glass decreased. It should be noted that the total quantity of glass varied between cases is small compared to the total building wall area (maximum of 8%), and yet the effect is significant.

CONCLUSION

The results presented in this paper are illustrative of the effects of a number of variables on the energy performance of several types of HVAC systems, all of which include optimum operation of the combined heat reclaim/economizer provisions.

As shown, the operating costs are influenced by such factors as type of system, local climate, thermal mass and thermal resistance of the building envelope, amount of fenestration, and internal heat gain level. Few general conclusions as to the relative savings of heat reclaim vs. economizer operation can be made. Each building, with its operating schedules, envelope, and geographical location, should be subjected to the analysis described.

In buildings with significant heating and cooling loads, heat reclaim systems normally will save more energy and have lower life-cycle costs than economizers. As a result, heat reclaim should take priority over economizer operation where significant heating and cooling loads exist simultaneously.

Heating fuel costs will have a significant impact on the cost savings difference between heat reclaim systems and economizers. As a result, the life-cycle cost advantage of heat reclaim over economizer operation will decrease for lower fuel costs and the preferred selection will likely switch from heat reclaim to economizer for buildings with little heating load and a low unit heating fuel price.

The methodology and computer algorithms developed for this stand-alone program should prove useful to system designers in selecting HVAC system energy-savings features. The loads and energy-estimating features of the program have been "verified" in comparison to a major mainframe, hour-by-hour energy analysis program, with the details covered by Anantapantula (1993).

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