Life-Cycle Cost Optimization of Residential Building Designs

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ABSTRACT

This paper describes a numerical whole-building optimization method that has been developed to optimize selected residential building envelope and equipment efficiency parameters, using life-cycle cost (LCC) as the optimization criterion. Details of the method are discussed, including the exploitation of special characteristics of the objective function, and its numerical implementation. The method is demonstrated by calculating optimal configurations for a typical single-family residence for a range of U.S. climates. Several potential applications are discussed, focusing on the development of energy standards, and energy performance guidance for design tools.

THE OPTIMIZATION METHOD

Approach

Under the limiting assumptions that externalities are accounted for and appropriate pricing of energy and materials resources is possible, then the life-cycle cost of a building is the correct objective function to minimize in order to achieve maximum economic efficiency. The effects of construction costs, expected utility costs, and other economic assumptions in determining the optimal configuration are accounted for in the LCC objective function.

Several characteristics of the life-cycle cost function specific to this application can be exploited to provide both more efficient techniques and more general results for the single-building optimization problem: First, the objective function can be succinctly expressed in terms of a single parameter, the "Conservation Index," which is a measure of the importance of annual operating costs relative to initial costs. Significantly, the optimal designs calculated for this type of LCC objective function depend only on the value of the Conservation Index. Next, it is shown that any specific economic scenario leads to a unique value of the Conservation Index. Consequently, optimal configurations can be systematically *pre-calculated* for a wide range of Conservation Index values and subsequently determined for any particular economic scenario by a simple look-up procedure. Finally, some applications require that the optimization be subject to either initial-cost or energy-consumption constraints. It is shown how optimal designs subject to such constraints can be derived in a simple way from unconstrained optimal designs using the Conservation Index, therefore making it unnecessary to calculate them separately once the unconstrained optima are known.

Life-Cycle Cost Minimization

The LCC Objective Function. The life-cycle cost objective function for a particular building design configuration can be expressed as:

$$LCC(\mathbf{D}) = F_1(C1(\mathbf{D})) + F_2(\mathbf{E}(\mathbf{D})), \qquad (1)$$

where F_1 and F_2 are scalar functions that express the particular economic relationships for the two components of the total life-cycle cost associated with (1) the initial construction cost $C1(\mathbf{D})$ of a house with a configuration that is describable by the set of design variables $\{d_i\}$ represented by the vector **D**, and with (2) purchased energy from utilities characterized by the vector $\mathbf{E}(\mathbf{D}) = [E_1(\mathbf{D}), E_2(\mathbf{D}), \cdots, E_M(\mathbf{D})]$ (which allows for the possibility of M energy use categories that require different fuel types). Each term represents the net effect of all cash flows in its respective category over the economic lifetime of the analysis, corrected for the time-value of money using present-value techniques [1].

The function F_1 accounts for the effects of all time flows of money, including cost components for financing, maintenance or periodic replacement of necessary parts of the structure or relevant equipment over the economic lifetime of the investment, the costs (or benefits) related to taxes and insurance, and resale benefits. Under reasonable assumptions, costs in the cash flow stream can be expressed as simple multiples of the initial cost $C1$ using appropriate present-value factors for each cost component. Thus $C1$ can be factored out of the sum of all terms, leaving a composite present-value multiplier that is not a function of $C1$:

$$F_1(C1(\mathbf{D})) = F_1 \cdot C1(\mathbf{D}). \qquad (2)$$

Once economic assumptions have been made for a particular optimization analysis, the present-value multiplier F_1 is a constant, and only $C1$ changes during optimization.

The purchased utility cost function has a multiplicative form analogous to that of the configuration cost:

$$F_2(\mathbf{E}(\mathbf{D})) = \sum_{i=1}^{N} PVf_i \cdot p_i \cdot E_i(\mathbf{D}) = \sum_{i=1}^{N} PVf_i \cdot U_i, \qquad (3)$$

where p_i is the unit utility price for fuel type i in the base year of the analysis, PVf_i is the present value factor for the stream of annual utility payments (which depends only on the assumed discount rate, fuel appreciation rate, and analysis lifetime), and U_i, the base-year utility cost. Note that the initial fuel price assumptions p_i are separated from assumptions about the future growth in those prices, which are contained in the PVf_i. The annual energy use components E_i are assumed to come from a full-year energy analysis based on long-term average weather conditions, and thus have a constant value during the analysis lifetime.

Incremental Life-Cycle Cost. Since at an optimum the partial derivatives with respect to all active decision variables vanish, the LCC objective function can be modified by one or more arbitrary additive or multiplicative constants without changing the corresponding optimum. Thus we can write:

$$\begin{aligned} \Delta LCC &= F_1 \cdot (C1 - C1_0) + \sum_{i=1}^{N} PVf_i \cdot (U_i - U_{i,0}) \\ &= F_1 \cdot \Delta C1 + \sum_{i=1}^{N} PVf_i \cdot \Delta U_i \end{aligned} \tag{4}$$

Here $C1_0$ and $U_{i,0}$ can be *any* constant values whatever, but are typically chosen to be the initial and base-year utility costs corresponding to some appropriately chosen "reference" configuration. $\Delta C1$ and ΔU can be interpreted as *incremental* initial costs, and *incremental* energy (or utility cost) savings, relative to the reference configuration. There are practical advantages during computation, and intuitive advantages during interpretation of the optimization results, if $C1_0$ and $U_{i,0}$ in Eq. 4, are chosen to be the lowest possible initial-cost configuration and its related energy consumption, thus making the reference a "minimally performing" configuration. The development of a reference configuration is discussed in the example below.

The Conservation Index. Another important consequence of the ability to modify the LCC objective function by an arbitrary constant without changing the optimal configuration comes from dividing through by the constant F_1:

$$\Delta LCC' = \Delta C1 + \sum_{i=1}^{N} CI_i \cdot \Delta U_i \,, \tag{5}$$

where $CI_i = PVf_i / F_1$, and $\Delta LCC'$ gives the same optimal configuration that ΔLCC does. The actual life-cycle cost can be recovered for any specific economic scenario once F_1 is known. $\Delta LCC'$, and thus the optimum configuration that results from it, depends only on the dimensionless *ratios* CI_i, which are a measure of the weightings that should be given to each of the base-year utility cost components relative to the initial cost. These ratios are termed the *Conservation Indexes* (CI's): larger CI values weight the importance of fuel costs more relative to the configuration costs, and thus lead to more energy-conserving optimal configurations.

The great practical significance of the Conservation Index concept lies in the fact that it is possible to pre-calculate optimal configurations in a systematic manner for a wide range of CI values, *without needing to know either the particular ownership* (F_1) *or economic and fuel futures* (PVf_i) *scenarios*.. The correct optimum for a particular economic scenario can be subsequently determined by calculating its CI_i values from PVf_i and F_1, and looking up the result. Although multiple fuel-type applications have the potential for requiring much pre-calculation to generate complete "multi-dimensional" look-up tables, for many applications fuel price increase scenarios lead to the approximately the same PVf_i's for different fuel types, (possibly predicated on fuel type interchangability and subsequent market competition), then there is only a single Conservation Index.

A prototypical reference scenario indicative of residential ownership of a single-family home assumes a 30 year analysis lifetime, 7.5% discount rate, 10% property appreciation rate, 12.5% nominal fuel price appreciation rate, 12% loan interest rate, 30% marginal income tax rate, a 2% nominal effective property tax rate, and a 90% loan for the same length as the analysis period. The calculated CI-value for this reference scenario is 25. Low fuel price increases and short lifetimes can lead to CI-values lower than 10. Conversely, an energy-conserving scenario corresponding to high fuel price increases and resale credits for the extra conservation investments can lead to CI-values higher than 100.

Constraints

Energy performance requirements based directly on an unconstrained LCC optimum leave no room for design flexibility since only the optimal configuration meets those requirements and has the minimal LCC. Thus, there is a need for a rational mechanism for "backing off" from such a rigid requirement, and that also provides a means for evaluating the economic consequences of such easing. Optimal configurations that are determined subject to constraints on either the incremental initial cost or the incremental utility costs provide such a mechanism, and are useful in this application.

It is possible to obtain optima subject to initial cost and energy performance constraints without having to directly calculate them using constrained optimization methods by exploiting the particular forms of the constrained LCC functions and the Conservation Index concept. The reasoning, verified by numerical testing, is as follows: The initial-cost constrained constrained LCC function can be written as:

$$LCC'_{C1} = \Delta U, \text{ (Initial Cost Constrained).} \tag{6}$$

At each value of CI, there is an optimum configuration, $\mathbf{D}^*(CI)$, with related optimal initial cost $C1^*(CI) = C1(\mathbf{D}^*)$, and base-year utility cost $U^*(CI) = U(\mathbf{D}^*)$. Thus, if calculations are made for sufficiently small increments over a sufficiently wide range of CI values, optimal results will be obtained that represent the entire corresponding feasible range of $C1^*$ and U^* values. Now, if any arbitrary but feasible value of $C1$ is selected as a constraint, then there is a corresponding unconstrained optimum configuration with that same value of $C1$ and a related U^*, and further, that U^* is the minimum U possible at initial cost $C1$. But by Eq. 6, this is just the definition of the requirement needed for a *constrained* optimum at initial cost $C1$. Thus, once an unconstrained optimum configuration is found for a particular CI that has an initial cost $C1^*$, this configuration is *also* the optimal configuration for the initial-cost-constrained problem at that same initial cost. An analogous argument can be made for base-year utility cost constraints (which can be related to energy performance budgets).

The Computerized Optimization Tool

Overall Structure. Several numerical and conceptual techniques needed to be developed in order to implement the method are described here. One was a fast energy simulation engine that properly accounts for the effects of climate and for the interactive effects on energy performance among multiple design parameters, thus allowing for their simultaneous optimization. Another was the embedding of the simulation engine into the broader context of a robust optimization procedure. A survey of available software led to the selection of numerical optimization routines developed by the Numerical Algorithms Group (NAG) at Oxford University for use in this study [2]. Figure 1 shows in conceptual form the numerical implementation of the optimization procedure. The components that comprise the objective function evaluation are shaded. Information interfaces between the optimization routine and the function evaluation consist of the configuration parameters $\{\mathbf{D}\}$, the life-cycle cost, and the constraint function values for any active constraints. The objective function evaluation consists of determining, for the building configuration represented by the vector of optimization variables $\{\mathbf{D}\}$, its annual heating and cooling requirements, annual base-year utility cost, and initial cost. Assumptions related to weather data, building operation and occupant behavior, construction costs, and utility rates are used as shown in various phases of these calculations. The base-year utility cost is derived from the building energy use. The utility cost and initial cost are then used, in conjunction with additional economic assumptions (typically in the form of a Conservation Index value) to calculate the life-cycle-cost objective function, which is passed back to the optimization routine in an iterative process until a satisfactory minimum of the objective function is found, which corresponds to the optimal configuration $\{\mathbf{D}^*\}$. As shown, constraints can be specified.

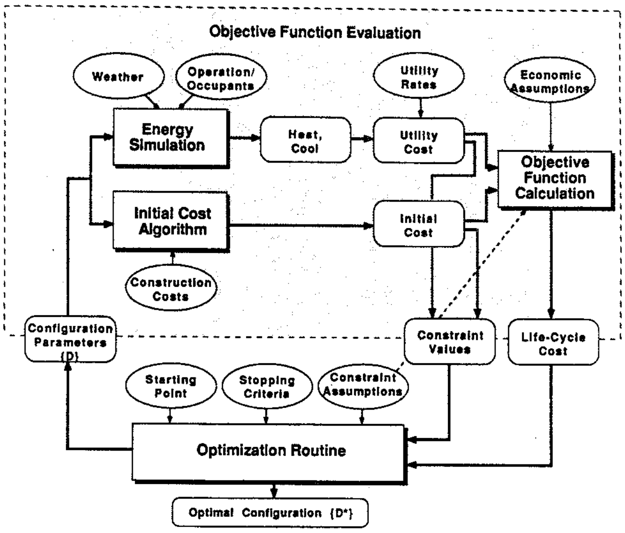

Figure 1. Conceptual diagram showing the relationships between the separate computational components of a comprehensive building optimization procedure, together with the related information flows.

BCEGY. The energy simulation model ("BCEGY" -- **Building Configuration Energy**) used for the objective function evaluation was specially developed for this application. It is based on the variable base degree-day (VBDD) method, a sufficiently complex physical model to account for all important energy use determinants, and at the same time having the potential for fast computation speeds through careful algorithm design and logical organization. BCEGY accounts for envelope heat losses and gains, internal heat gains, solar and sky radiation effects, thermal mass and thermostat setbacks, and ventilation strategies, and detailed furnace and air conditioner models. The capacities of the furnace and air-conditioner are automatically sized based on the peak loads of the space and a specified maximum time requirement for morning recovery from night setback temperatures. BCEGY runs a complete annual analysis in about 0.1 second on a 10 MIPs computer, and was carefully designed to produce simulated results that are numerically smooth, continuous functions of the design variables, a characteristic necessary for reliable optimization results. Algorithm and implementation details of BCEGY, including a comparison to other verified simulations, are described in [3].

AN EXAMPLE

In this section, the optimization methodology is demonstrated for a typical single-family detached residence. Design and cost assumptions for the residential prototype are described. A reference configuration is defined. Calculated optimal configurations are presented as a function of incremental initial cost, and their characteristics analyzed and discussed. The climate dependence of calculated optimal configurations is also discussed.

Description

Design and Operation Assumptions. The house used for this study is a one-story $1200\,ft^2$ wood-frame frame construction with insulated walls and ceiling.and a vented, unconditioned attic, and is prototypical of much single family residential construction in the U.S. [4,5]. The design assumes a concrete slab-on-grade floor construction, and windows in the exterior walls on all four sides. The house is assumed to be heated with a gas furnace and cooled with electric central air conditioning, which share a fan-driven forced-air duct distribution system. Other assumptions include typical internal loads for occupants, lights and appliances, thermostat settings of 78 °F for air-conditioning and 68 °F for heating, with a floating deadband in between, a nighttime set back to 55 °F, natural ventilation whenever the outside air temperature is below the cooling thermostat setpoint, and shades and/or blinds that on average reduce the net solar gains through windows by half [3].

Optimization Parameters. Eight design variables were selected as optimization parameters based on their impact on energy use. They are the thickness of (1) wall insulation, (2) ceiling insulation, (3) floor insulation; (4) the number of window panes (a continuous, not a discrete, variable), and (5) the North/South window distribution, a single parameter representing the fraction of the (fixed) total North and South window area that was oriented South; (6) the infiltration rate, measured as a volumetric air exchange rate between inside and outside air; (7) the overall furnace conversion efficiency, and (8) the air-conditioner Coefficient of Performance (COP). The last two parameters were specifically included to allow the optimization procedure to simultaneously trade off equipment conversion efficiency against both increased equipment cost and against the other six envelope parameters. All parameters were restricted to physically meaningful ranges, as described in [3].

Cost Assumptions

Incremental cost estimates that were used in this study are summarized in Table 1. The configuration initial cost is determined from incremental costs for materials, labor, or any other sources, to reach a particular level of each of the optimization parameters. The total base year utility cost is determined from the energy use and estimates of the incremental unit utility rates for each fuel type. In order to determine optima from the perspective of the home buyer, typical total contractor installed costs included overhead and profit. All figures are meant to represent national averages, expressed in 1985 U.S. dollars.

Special features of the cost calculation include a framing model that realistically adjusts stud spacing and framing design with the amount of wall and ceiling insulation, and infiltration costs approximate a smooth function of the air infiltration rates, representing construction that does nothing to reduce air leakage above about 1 ACH, to caulking, weatherstripping, and vapor barriers at intermediate infiltration rates, to the installation of an air-to-air heat exchanger at infiltration rates below about 1/2 ACH.

It was not possible to find direct costs for manufactured window units with more than three panes, thus the average incremental cost estimates based on single, double, and triple-pane window cost data were assumed to be the same for all window thicknesses. This assumption is probably optimistic, and thus leads to optimal configurations that might require more window panes than current practice would actually dictate. However, if these assumptions lead to optimal windows with many panes, it has the useful effect of pointing out a market opportunity for new products of this type, and thus indicate an area where a government policy might be implemented to provide the necessary incentives.

Table 1. Incremental Initial Cost Estimates

Component	Incremental Cost	Reference
Wall Insulation	$\$0.053/ft^2 \cdot R\text{-}unit$	[6,7]
Ceiling Insulation	$\$0.019/ft^2 \cdot R\text{-}unit$	[6,7]
Floor Insulation	$\$0.071/ft^2 \cdot R\text{-}unit$	[7,8]
Windows	$\$2.50/ft^2 \cdot pane$	[7,8]
Infiltration	$\$20./ACH^3$	[8,9]
Furnace	\$0.72/kBtu/hr @ $\eta = .55$	[8,10]
	\$1.46/kBtu/hr @ $\eta = .80$	
Air Conditioner	\$430/ton @ COP = 2.0	[10-12]
	\$750/ton @ COP = 3.5	
Fossil Fuel	\$7.50/MBtu	[13]
Electricity	\$24.00/MBtu	[14]

Results

Reference Configuration. There are two candidates for the reference configuration against which the performance of the optimal configurations can be compared. The first candidate is a fixed-design, "minimal" configuration which has no insulation, single-pane windows equally distributed between North and South, a relatively leaky 1 ACH infiltration rate, and low equipment efficiencies. However, even this Minimal Configuration might not have the lowest initial cost. Using our computerized optimization methodology and setting the Conservation Index to zero, it is possible to determine a second, "least initial cost" candidate reference configuration. Table 2 summarizes comparisons between these Minimal and Least Cost candidate reference configurations for three cities that represent a range of U.S. climates.

The results of the least-initial cost optimization are surprising and significant. First, the Least Cost optimum configuration is not only less expensive than the Minimal Configuration in all climates, it also uses significantly less energy and has correspondingly lower base-year utility costs (10% to 25%). The Least Cost optimum configuration adds a small amount (R2 to R3) of ceiling insulation, reducing the infiltration rate to about 3/4 ACH, and orients the maximum possible amount of windows to the North. These configuration changes reduce peak loads, and thus the furnace and air-conditioner sizes and initial costs. The equipment size reductions provide the initial cost savings that pay for the increased costs of the insulation and infiltration changes.

Table 2. Comparison of Reference Configuration Candidates

Parameter/ Quantity	Minimal Configuration	Least Cost Configuration		
		Minneapolis	New York City	Miami
Wall Insulation (R)	0	0	0	0
Ceiling Insulation (R)	0	3.4	3.4	2.2
Floor Insulation (R)	0	0	0	0
Infiltration (ACH)	1	.72	.75	.70
Window Panes	1	1	1	1
Window Distribution	.5S/.5N	N	N	N
Furnace Efficiency	.55	.55	.55	.55
A/C COP	2.0	2.0	2.0	2.2
Δ Fur. Size (kBtu/hr)		-51	-33	-11
Δ A/C Size (kBtu/hr)		-7	-4	-9
Δ Utility Cost ($/yr)		-713 (-26%)	-386 (-26%)	-104 (-9%)
Δ Initial Cost ($)		-159	-74	-226

There are significant energy- and cost-performance differences between the Minimal Configuration and the Least Cost configuration (which varies with climate), and it was chosen as the reference against which the unconstrained optimization parametric runs are compared.

Optimal Configurations as Function of Initial Cost. Optimal configuration results from our method are shown in Figure 2 for Miami and New York City, plotted as a function of incremental initial cost. The resultant optimal configuration at each level of initial cost has the the lowest base-year utility cost, hat can be achieved for that particular initial cost level. It is important to remember that the optimal configuration at any specific initial cost level is an unconstrained optimum for only *one* economic scenario, namely the one that corresponds to the initial cost for the particular CI-value corresponding to the economic scenario of interest. The actual optimal initial cost to be used can be determined from the corresponding CI-value from subplots (e). For example, using the CI-value of 25 for the typical residential economic scenario described earlier, the corresponding optimal incremental initial cost investments are seen to be about $3000 and $4000 for Miami and New York City, respectively. Figure 2 can be used as a nomograph, starting with a CI-value on the ordinate axis of subplot (e), finding the corresponding optimal initial cost from the horizontal axis of this subplot, and, projecting vertically upward, finding the optimal configuration parameter values from the subplots (a-d) aligned vertically above.

An important result is that the optimal levels for the configuration parameters are higher than a typical current practice design, which would correspond to unconstrained optima for CI-values of only 8, 15, and 20, for Minneapolis, New York City, and Miami, respectively. Since even typical economic scenarios correspond to higher CI-values than that, the optimal configurations have significantly better energy performance. These optimal values confirm the need for high ceiling insulation levels, even in warm climates. The results also indicate optimal window thicknesses with significantly more panes, particularly in hot climates, indicating the importance of solar-gain avoidance when cooling energy and consequent electricity costs are accounted for in the optimization procedure. For Miami, the all-North distribution is always optimal. Such a distribution minimizes solar gains, which is the primary determinant of this parameter when cooling loads predominate or when initial costs are significantly more important than utility costs. Thus, the analysis provides important quantitative qualifications to the popular design rule which always dictates orientation of maximal window areas toward the South in preference to the North. Optimal infiltration levels are low enough to require the use of air-to-air heat exchanger technology for their achievement for many economic scenarios.

Another feature of the optimal configurations concerns equipment efficiencies. While the optimal efficiencies for heating equipment are either at their maximum or minimum limits, the optimal cooling COP's are less than the maximum limit for a wide range of optimal configurations that might be expected to be encountered as reasonable economic scenarios. This result is significant because an isolated life cycle cost analysis of either the furnace or air conditioner might well have indicated that maximum efficiencies are optimal for these same economic assumptions [10]. However, when the marginal costs and benefits of investment in increased equipment efficiencies have to compete with the additional simultaneous alternative investments of the present analysis, maximum equipment efficiency is not always optimal.

APPLICATIONS

There is a wide range of uses for a general building life-cycle cost optimization methodology, which in the aggregate could result in information that has a significant potential for increases in economic efficiency and in reductions in energy consumption, and can also provide specific evaluation mechanisms that could greatly increase the ease and feasibility of implementing policies that would lead to actual realization of the potential for energy savings in buildings.

One important application area is the development of building energy standards, including the rational setting of energy budgets, evaluating the impacts due to their implementation, providing ways of incorporating design flexibility into standards, determining economic inefficiencies resulting from non-optimal current design practices, and determining what types and amounts of incentives are justified. Specific uses include:

- Provide information for the development of energy standards (of both the prescriptive and performance types), and mechanisms for evaluating the impact of their implementation.

- Provide a rational, quantitative mechanism for evaluating economic inefficiency resulting from non-optimal current design practices.
- Provide ways of rationally building flexibility into building energy standards.
- Identify new design and/or construction techniques and related new products not currently available that need to be developed or marketed in order to build optimally designed buildings.
- Provide rational, quantitative mechanisms to determine what types and corresponding levels of incentives are justified to encourage new building designs and new product development.

Another general application area is that of providing optimal parameter information during the building design process as one component of an advanced, interactive design tool. The fast numerical techniques that characterize our optimization method would lend themselves especially well to providing the immediate feedback that this type of application requires, by updating optimality information essentially as fast as the user could interactively change the building design. Specific uses include:

- Identify optimal configurations for the design community, and thus ways of designing buildings that meet or exceed the energy budget requirements of standards.
- Provide information to designers regarding the best way of optimally allocating costs to various design features in order to achieve prescribed performance levels.
- Provide design trade-off mechanisms that maintain optimality.

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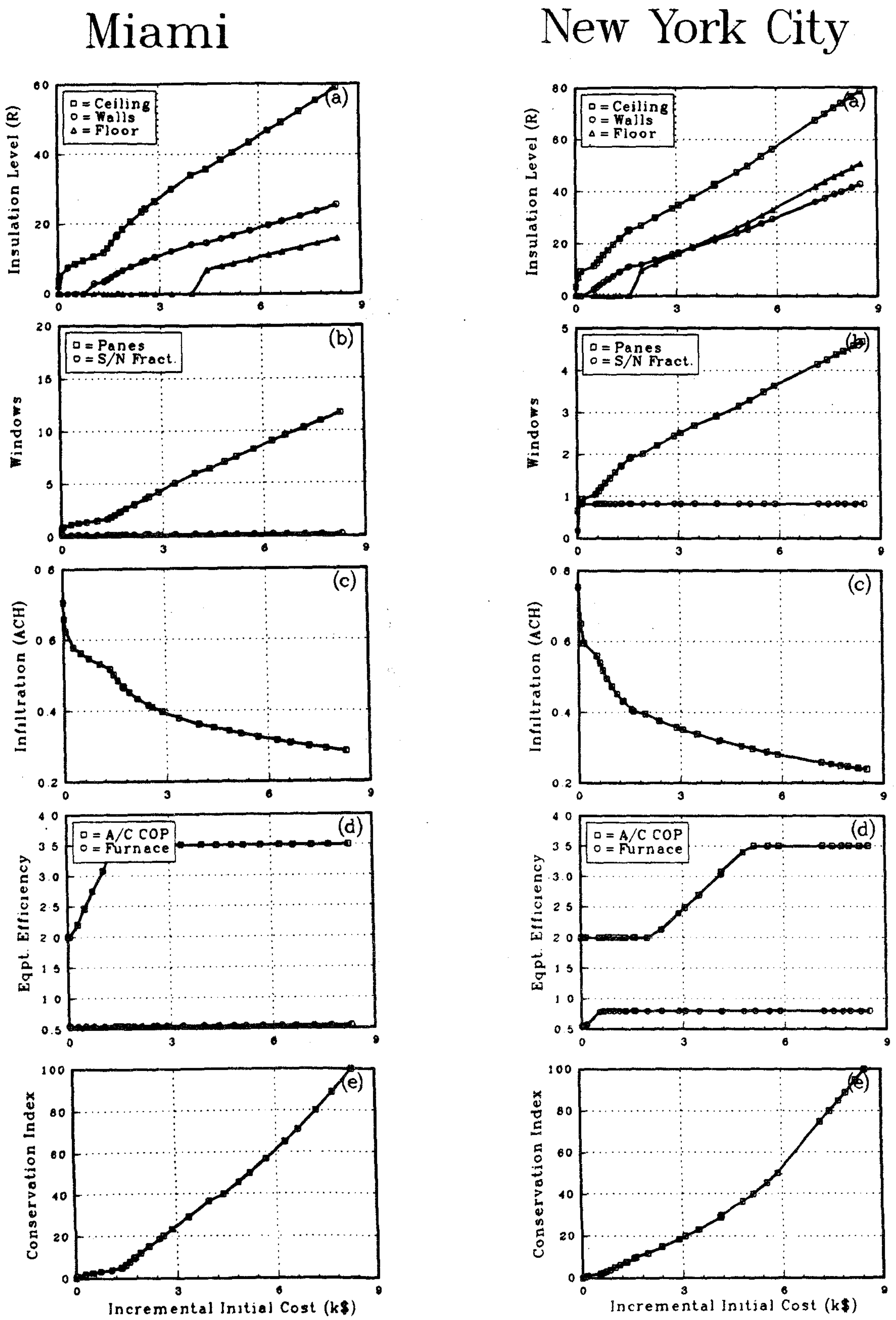

Figure 2. Plots of optimal configurations as a function of the incremental initial cost for Miami and New York City. Subplots (a-d) are optimized configuration parameters; subplots (e) relate optimal incremental initial cost to CI-value. Note that while the configurations are optimal at each incremental initial cost, only one incremental initial cost, and thus one configuration, is optimal for a particular CI-value (which in turn is determined from a particular economic scenario). This figure can be used as a nomograph, starting with a CI-value on the ordinate axis of subplot (e), finding the corresponding optimal initial cost from the horizontal axis of this subplot, and, projecting vertically upward, finding the optimal configuration parameter values from the subplots (a-d) aligned vertically above.