A DECISION MODEL FOR THE DESIGN OF BUILDING ENVELOPES

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ABSTRACT

Building envelopes are required to perform a combination of structural, space-enclosing, and environmental protection or modification roles. The properties of the materials utilized in their construction modify the effects of macroclimate on the interior of the building. Every year a whole new range of materials having applications in building industry appears on the market. Often only a limited amount of information is available regarding these new materials from the manufacturer's own literature. In such circumstances the design of building envelopes that should be composed of appropriate materials to satisfy various performance requirements become difficult.

In this paper the thermal performance of building envelopes is considered along with other quantitative performance measures, such as cost, capital energy consumption, and structural efficiency, and an approach to the resolution of conflicting demands through multicriteria decision methods is described. The approach generates prescriptive quantitative information at the early stages of architectural design to aid the designer in making decisions. An example of the design of building envelopes is presented in detail.

INTRODUCTION

Materials utilized for building envelopes are typically multifunctional in nature, required to perform a combination of structural, space-enclosing and environmental protection (heat, noise, etc.) or modification roles. Users of existing materials have a working qualitative knowledge of their performance characteristics from the available literature and current practices, but they generally choose a material on the basis of only one or two performance functions. For example, a material may be selected on the basis of its heat transfer characteristics while ignoring its effects (good or bad) on capital energy consumption and noise penetration functions. Such an approach ignores the multifunctional characteristics of materials. That is, independent material layers are specified for each functional requirement as a solution, and an envelope may finally result in six to eight layers, thus, leading to excessive amounts of material consumption, prolonged construction time, and excessive cost. From a rational design standpoint, building envelopes need to be designed to achieve the best possible balance of performances in all the functions to be fulfilled.

Krokosky (1968, 1971) has proposed a procedure to solve this multifunctional design problem by making random search through a ranking matrix reflecting the performance of each alternative in each function on a scale between most and least desirable values. This procedure assumes that any design solution is as desirable as its least deasirable performance in any function. All the material properties were assumed to be continuous functions of density and expressed in terms of this property. It is not entirely realistic to express discrete properties of materials as continuous functions of density. Such an assumption is unlikely to identify an optimal multifunctional material that exists in reality.

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As an alternative, Rao et al. (1973) and Mattar et al. (1978a, 1978b) present decision models based on utility theory. By assigning weights to various material properties, Rao et al. enable the designer to grade on the basis of a material's suitability for the design situation. The optimum material design parameters are found by means of maximum expected utility criteria. Mattar et al. present a model for existing material systems that utilizes utility transformations to normalize performance in each function. The solution set is reduced through Pareto optimization and a best solution (or solutions) is identified by the operation of preferences among functions. The procedure assumes that the designer can weakly order the importance of these functions, that each function is independent, and that the best set of performance lies among those performance combinations defining a convex set in the performance space, a subset of the Pareto set.

From a building designer's decision-making standpoint, his requirements are to have design information that is prescriptive, expresses design options, and addresses the problems of the stability and sensitivity of solutions, thus providing insight and understanding to him for making a decision. A decision model for the design of building envelopes presented in this paper addresses these issues by utilizing multicriteria optimization, cluster analysis, and inverse goal programming. The model takes into consideration the properties of materials and relates these to the functional requirements of building envelope. A two-level procedure is adopted here: the first level identifies the material systems with multifunctional performance characteristics for the building elements and the second level utilizes the material systems so identified to enclose a space (Figure 1).

MULTICRITERIA DESIGN

Various disparate performance requirements characterize material system design, each of which may be in a different unit, such as sound transmission loss in decibels, rate of heat flux in watts/(meters square x hours), cost in dollars, etc. Clearly it is not possible to add each of these directly, even if expressed in the same terms, say dollars. For example, one dollar's worth of increase in sound transmission loss is not the same as one dollar's worth of decrease in rate of heat flux. What needs to be known is the minimum amount of one kind of performance. Such conflicts and trade offs can be considered in multicriteria design.

The following terminology associated with multicriteria design is defined:

1. Decision (or solution) space contains the description of all solutions. A design solution to a problem with N decision variables can be uniquely represented as a point in N-dimensional space (Figure 2);

2. Criteria (or performance) space contains the description of all performances. The performances of a solution to a problem with P criteria can be represented as a point in P-dimensional space (Figure 2);

3. Constraint set contains the description of all restrictions that limit the range of decisions or performances;

4. Criteria or objectives are measures of performance that can be non-commensurable, e.g., cost in dollars, mass in kilograms, energy in megajoules. It is the designer's responsibility to identify appropriate criteria consistent with his design aims;

5. Goal is a general evaluative statement; which the building designer strives to achieve. Examples are: economical buildings, environmental comfort, etc.

6. The non-inferior, non-dominated, or Pareto optimal solution set is a subset of feasible solutions for each of which no other feasible solution exits, which will yield an improvement in one criterion without causing a degradation in at least one other criterion. In Figure 2, if we adopt the convention that increasing distance from the origin corresponds to increasing desirability, A is better than B in criterion 1 and B is better than A in criterion 2 in the figure. Consider now, solution C. Solution A offers better performance in both criteria 1 and 2 than does C, and we can therefore state that C is dominated by A. If we identify the set of all solutions that are not dominated by any other solutions in both criteria, we find that their performance lies along a boundary of the performance space. They are known formally as the set of non-inferior, non-dominated, or Pareto

optimal solutions (Figure 3). The word Pareto has come to be associated here because such a principle was originally presented in welfare economics by the Italian economist Vilfredo Pareto (1848-1923) (Cohon 1978);

7. A trade off implies that the decision involves giving up, in quantitative terms, a certain amount of one performance in order to gain some amount in one or more of the other performances;

8. The most attractive solution is that solution which most appropriately reflects the design goals according to the designer's judgement.

A DECISION MODEL

The decision model integrates multicriteria Pareto optimization, cluster analysis, and inverse goal programming (Figure 4).

Given a set of criteria, constraints, and prediction models, multicriteria Pareto optimization prunes the decision and criteria spaces by eliminating dominated solutions. The choice of optimization technique is related to the particular design problem, but multi-criteria dynamic programming (Rosenman and Gero 1983) is attractive for problems that are characterized by nonlinearity and by discrete and/or discontinuous variables. For some problems, exhaustive enumeration of the decision space is feasible.

Cluster analysis reduces a large Pareto set to a smaller subset of strategic options. In cluster analysis, groups of solutions with similar performance characteristics are replaced by a single typical representative (Anderberg 1973). This is an integral part of the multi-criteria dynamic programming methodology, where necessary for computational feasibility, but can also be used as a part of the processing of the resulting set.

Trade off diagrams are used to display results in graphical form. The presentation of multicriteria optimization results in a meaningful manner is quite difficult, especially when there are large numbers of criteria involved. The approach adopted here is to present the N-dimensional multicriteria optimization results as two-dimensional trade off diagrams. Through these diagrams it becomes possible to show the trend of design solutions and their relative performances (Radford and Gero 1980). These two dimensional trade off diagrams allow the designer to examine the Pareto set for each pair of criteria as well as the Pareto set for all N-criteria.

For the design solution there are both qualitative performance information and detailed quantitative performance information available from the trade off diagrams. Qualitative performance information is provided by the scatter and the shape of the Pareto set on the trade off diagrams. On the other hand, by referring to the axes of these diagrams, quantitative performance information about the solutions in each criterion can be ascertained. These diagrams thus provide the designer with an opportunity to extract the kind of information that takes into consideration the interrelationships between various criteria functions simultaneously.

Inverse goal programming (Gero et al. 1982) provides a vehicle for interactively exploring the criteria space by asking "what if?" questions on the effect of applying desirable constraints to any combinations of the criteria. This has the effect of further pruning the decision and criteria spaces. The final selection of a most attractive solution by the designer is based on the above exploration. The methodology leaves selection of a particular solution entirely in the province of the designer.

PERFORMANCE REQUIREMENTS UNDER CONSIDERATION

In general terms, the important functions of the external envelope of a building are to act as a selective filter separating internal volume from external environment, excerise environmental control by modifying various aspects of macroclimate, and serve a structural function by resisting various loads. The performance requirements that have been considered here (Figure 1) are the ones with which the designer is most commonly concerned in an urban environment and temperate climate. A brief description of these is given here.

Thermal

In building design, thermal considerations make a great impact on the satisfactory performance of buildings. The thermal environment results from the interaction of the enclosed space with the external climate, thermophysical properties of the enclosing structure, and the occupancy, lights, and equipment usage within. Building envelopes effect modifications to outdoor thermal environment resulting in changes in the amplitude of variation and the timing of maximum-minimum temperature. These changes occur because building elements neither heat up nor cool down instantaneously. The ratio between the temperature amplitude of the material and external surfaces, known as the attenuation factor, and the time lag between their maximum and minimum express the thermal properties of building elements, while thermal transmittance is a useful parameter for comparing the relative insulating qualities of materials when the heat storage characteristics of building envelope are ignored. Therefore, these have been identified as performance criteria at level I.

At level II the impact of material systems on operational energy demand is considered. Buildings consume energy to maintain comfort conditions. Operational energy is then the energy consumed in supporting comfort conditions, which could be by maintaining HVAC plants, lift facilities, and lighting levels, etc. The impact of different building material systems used for the building envelope have bearing on the comfort of the occupants, as well as on the economical efficiency of the control systems (Givoni 1976).

There are two phases associated with the calculation of operational energy consumption. First is the consumption of that part of the operational energy demand related to thermal control, more commonly referred to as thermal loads. These comprise of heat transfer through the building envelope due to the external environment, comprised in turn of air temperature and solar radiation, infiltration, and ventilation, and internal loads due to occupancy. The second phase is the prediction of energy consumed in responding to these loads by HVAC plants so as to maintain thermal comfort conditions. Thus, the first phase concerns the minimization of the thermal loads imposed on plants by proper building design, whereas the second phase concerns the optimum design of an energy-consuming HVAC plant to cope with these loads (Clarke 1978). Concern here is restricted, however only to the effect the choice of material systems for building envelopes has on the thermal loads and their consequent impact on overall design decisions while considering other performances.

To assist the designer at the sketch design stage with quantitative design information with respect to the operational energy demand associated with the building envelope (opaque surfaces only), a computer program based on the IHVE guide (UK) was developed (Murthy 1983). This program takes into account the dynamic behavior of building elements in response to thermal inputs, and consequently, operational energy demands are estimated for space enclosed by different material systems.

Resource Conservation and Structural Consideration

Capital Energy Conservation. In the context of the building industry, energy resources are needed in the manufacture of materials, their transportation and construction, and to sustain life within the building. The study of energy in relation to building can be considered in two parts, one dealing with the amount of energy consumed up to the stage of putting up a finished structure, known as capital energy, and the other part taking into account the operational energy consumption during the building's lifetime. Here only the capital energy consumption is considered to identify building envelopes that are "better" or "worse" in terms of resources conservation.

Material Resource Conservation and Structural Consideration. Materials used for building envelopes could be conserved in a number of ways: by substituting readily available materials for scarcer ones; by using material systems having multifunctional capabilities; by rationalizing construction techniques and reducing wastage; by reducing the amount of material consumed, if feasible, through better design; by utilizing naturally available materials such as timber; by making use of by-products and recycling materials from demolished buildings.

The reduction in the mass of material consumed serves a two-fold purpose. Apart from being a conservation measure, it is beneficial from structural and foundation design considerations as well. The primary function of the structure is that of resisting forces and the primary force imposed is that caused by gravitational attraction. The gravity force is directly proportional to the mass. It may further be subdivided into dead loads and live loads. As the dead loads are permanent in nature, any reduction in mass would directly contribute to the design of economical structural sections.

Cost Model

The cost model considers only the material costs and assumes that cost has a linear relationship to thickness for each material layer present in the building envelope.

Space Utilization

Rentable space within a building would be wasted if it is to be occupied by an oversized building envelope. To take account of this, the overall thickness is identified as a criterion.

EXAMPLE: THE DESIGN OF MULTIFUNCTIONAL BUILDING ENVELOPES

The example presented here demonstrates the operation of the multicriteria optimization approach to the design of multifunctional building envelopes. As mentioned previously, a two-level approach is adopted here.

Level I

At this level the criteria space represents the various functional requirements of the material system and in the optimization process these are to:

- minimize thermal transmittance;
- minimize attenuation factor;
- maximize time lag;
- minimize capital energy consumption;
- minimize cost;
- minimize mass;
- minimize thickness.

The design variables that have been identified are the thicknesses of each layer comprising the material system and the material properties of these layers. These variables are within the control of the designer, and it is up to him to define the boundaries of the design space.

The materials with their thicknesses available to the designer are as follows:

MATERIAL CODE	MATERIAL	THICKNESS IN mm
1	Brick	90 100 115 200 230
2	Concrete	60 75 90 100 115 125 140 150 165 175 180 200 230
3	Color-coated corrugated sheeting	0.5 0.65 0.8 0.9
4	Rockwool insulation	20 25 50 75
5	Polyurethane insulation	20 25 50 75
6	Asbestos cement sheet	4.5 6 8 10
7	Air gap	50 100
9	Lightweight concrete block	100 200
10	Plaster board	10 16
11	Plaster	16
12	Gypsum board	10 16

The suitability of materials for exposure to the internal or external environment, and aesthetic considerations, limit the designer's choice as follows:

first layer (exposed to the external environment):
brick or concrete or color-coated corrugated sheeting.
second layer:
air gap, brick, rockwool insulation, asbestos cement sheet, or polyurethane insulation.
third layer:
concrete, lightweight concrete block, brick, air gap, or rockwool insulation.
fourth layer: (exposed to the internal environment):

brick, concrete, color-coated corrugated sheeting, gypsum board, plaster board, or plaster.

Initial Pareto Optimization and Cluster Analysis

For each layer of the building element, there are 15 combinations of materials and their thicknesses as variables and the total number of feasible solutions is 15^4, or 50,625. For 7 different performance criteria, the number of performance calculations to be performed would then be 7 x 50,625, or 354,375. For the same problem, solved by dynamic programming with Pareto optimization and cluster analysis, the number of computations carried out after four stages (for four layers) is 1,395.

There are 199 Pareto optimal solutions to this problem. From the theory of multi-criteria decision-making, the most attractive solution must lie among this set of Pareto optimal solutions. The presentation of results becomes very difficult when there are more than two or three criteria under consideration, and in this example there are seven. The approach adopted here is to display them as six two-dimensional projections of the seven-dimensional criteria space, using mass as the common axis on each projection (Figure 5). Mass is selected as the most important criterion in this case, but the designer could interactively choose to display graphs with any other pair of axes. A complete set, in this example 21 graphs, is shown elsewhere (Murthy 1983). Through such diagrams, it becomes possible to show the trend of design solutions and their relative performances (Figure 6).

Inverse Goal Programming: Constraints on Decisions and Performances

Using inverse goal programming, the designer can interactively explore the decision and criteria space. The following thermal performance constraints were applied:

- U-value < 1.0 W/m^2.°C
- Attenuation factor < 0.68
- Time lag $> 4.0 < 10.0$ hr

The number of Pareto optimal solutions is now reduced to 49 (Figure 7). Whether the effects on mass, capital energy consumption, cost, and thickness are acceptable would depend, of course, on the designer's priorities. If acceptable, then the performance of these 49 material systems in cost, capital energy consumption, U-value, attenuation factor, and time lag will be utilized as design variables at level II.

Level II

At this level the performance criteria identified to reflect the requirements of an enclosed space in the optimization process are to:

- minimize the total operational energy demand;
- minimize the operational energy demand for cooling;
- minimize the operational energy demand for heating;
- minimize the capital energy consumption;
- minimize the total cost.

The material systems are assumed to enclose a rectangular parallelopiped shaped building with five opaque surfaces. By considering each Pareto optimal solution one at a time for all the walls but keeping the roofing construction the same always, a set of 49 solutions are generated. Pareto optimization is performed on these solutions to identify the non-dominated solution set by utilizing the Pareto data base manager (CARU 1983). These Pareto optimal solutions are displayed as trade off diagrams (Figure 8). A performance interrelationship matrix, similar to that of Figure 5, can be developed at this level, and by utilizing the interactive technique of inverse goal programming, as shown at level I, the designer can explore the criteria space to identify the most attractive solution.

DISCUSSION

For the design solution there are both qualitative performance information and detailed quantitative performance information available from the trade off diagrams. Qualitative performance information is provided by the scatter and shape of the Pareto set on the trade off diagrams. On the other hand, by referring to the axes of these diagrams, quantitative performance information about the solutions in each criterion can be ascertained. These diagrams thus provide the designer with an opportunity to extract the kind of information that takes into consideration the interrelationships between the various criteria functions simultaneously. By operating on the trade off diagrams, the designer chooses the most attractive solution, or a set of these, that satisfies his requirements. To assist him in making his selection, an interactive approach is possible using inverse goal programming. Here the designer specifies his requirements in quantitative terms as lower or upper bounds, commensurate with his goals, on criteria and/or decisions under consideration. By releasing or tightening the bounds, he explores and manipulates the criteria space that consists of Pareto optimal performances until the most attractive solution, or a set of these is identified.

CONCLUSION

In this paper the design of building envelopes is presented as a multivariable multicriteria design problem, and a decision model comprising multicriteria Pareto optimization, cluster analysis, and inverse goal programming is presented for its solution. This approach allows the building designer to articulate his judgement at an operational level without making any explicit trade off or preference assumptions. The model makes it possible to approach the design of building envelopes in a much more integrated manner by considering more than one performance requirement than is possible with existing discrete simulations or single criterion optimization techniques.

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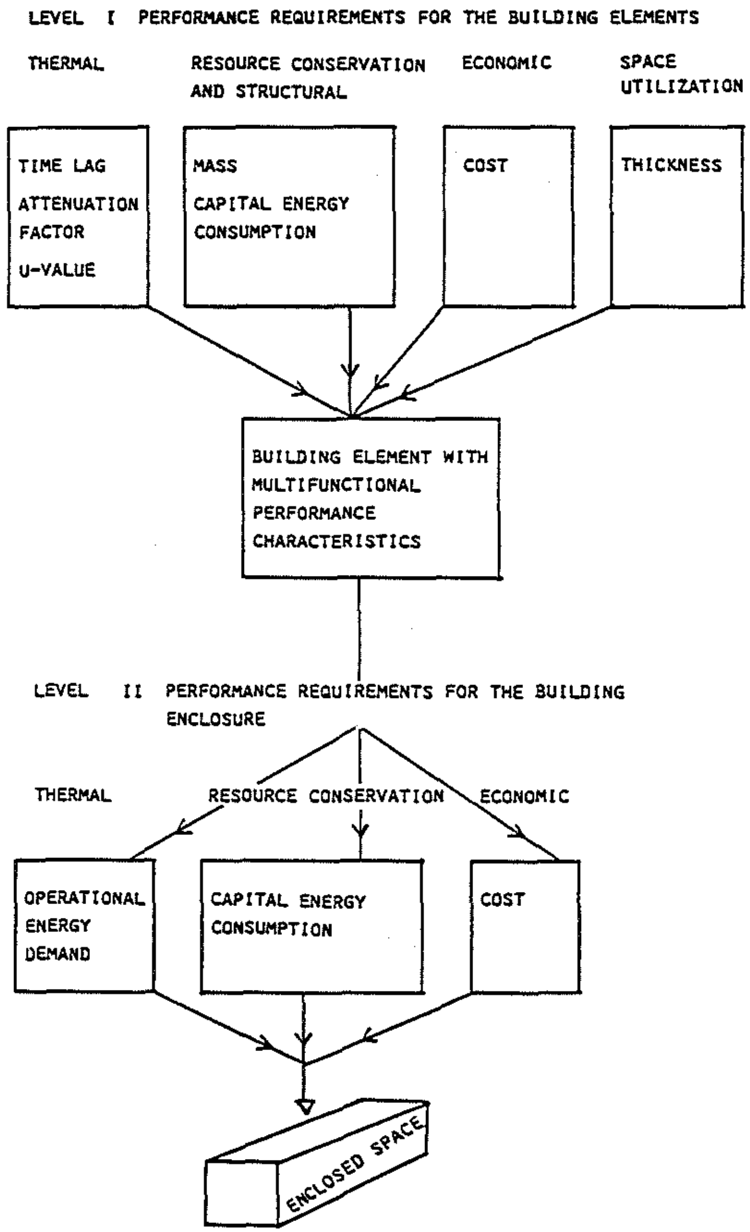


Figure 1. Two-level approach to design of multifunctional building envelopes

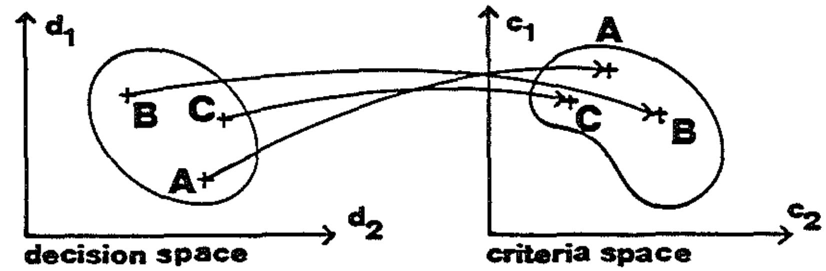


Figure 2. Decision space and criteria space for two decision variables and two criteria

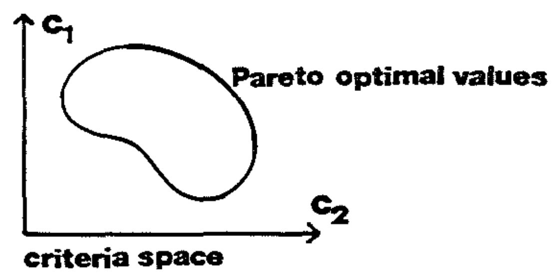


Figure 3. Pareto set in two-dimensional criteria space

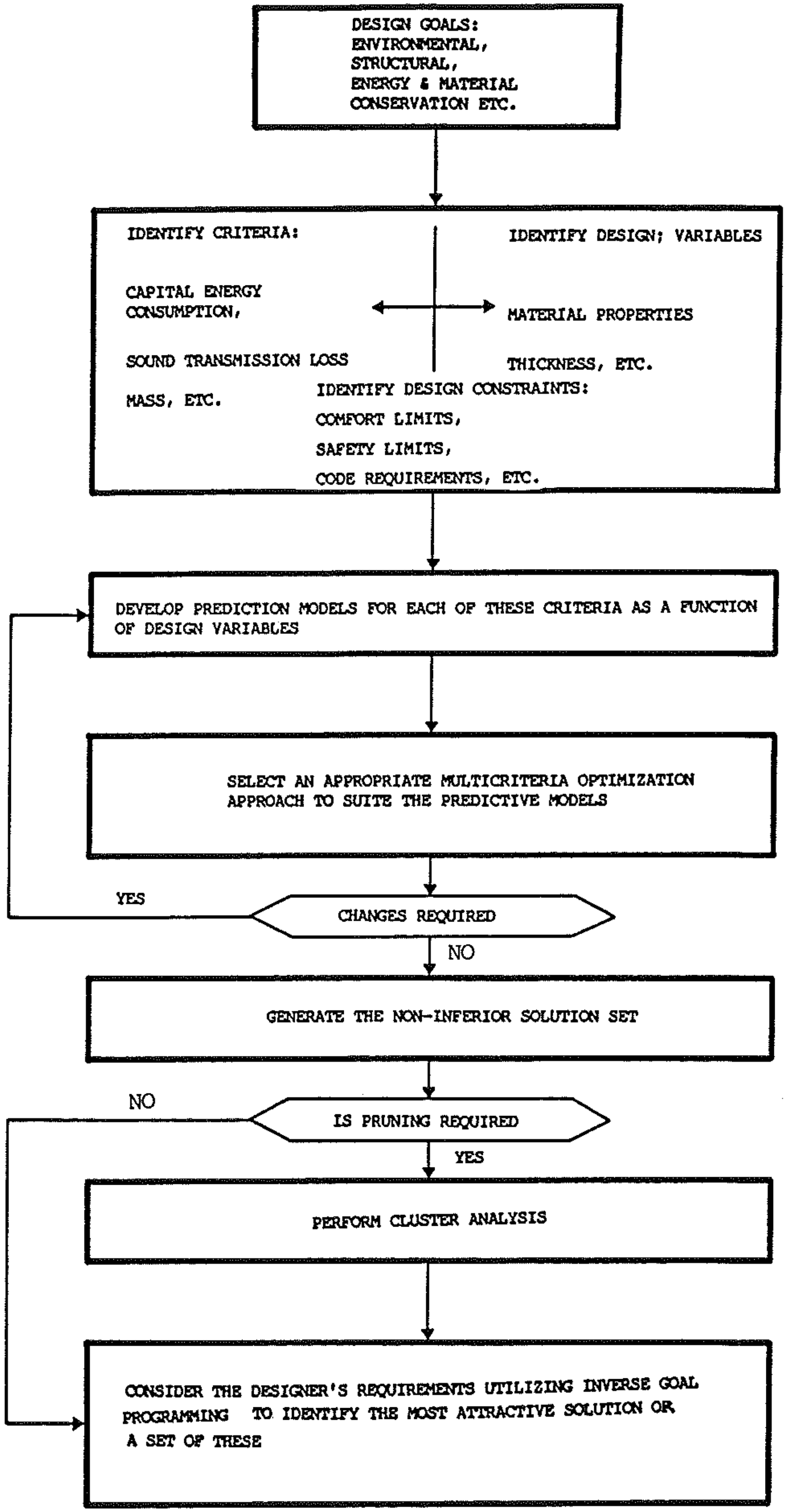


Figure 4. Decision model

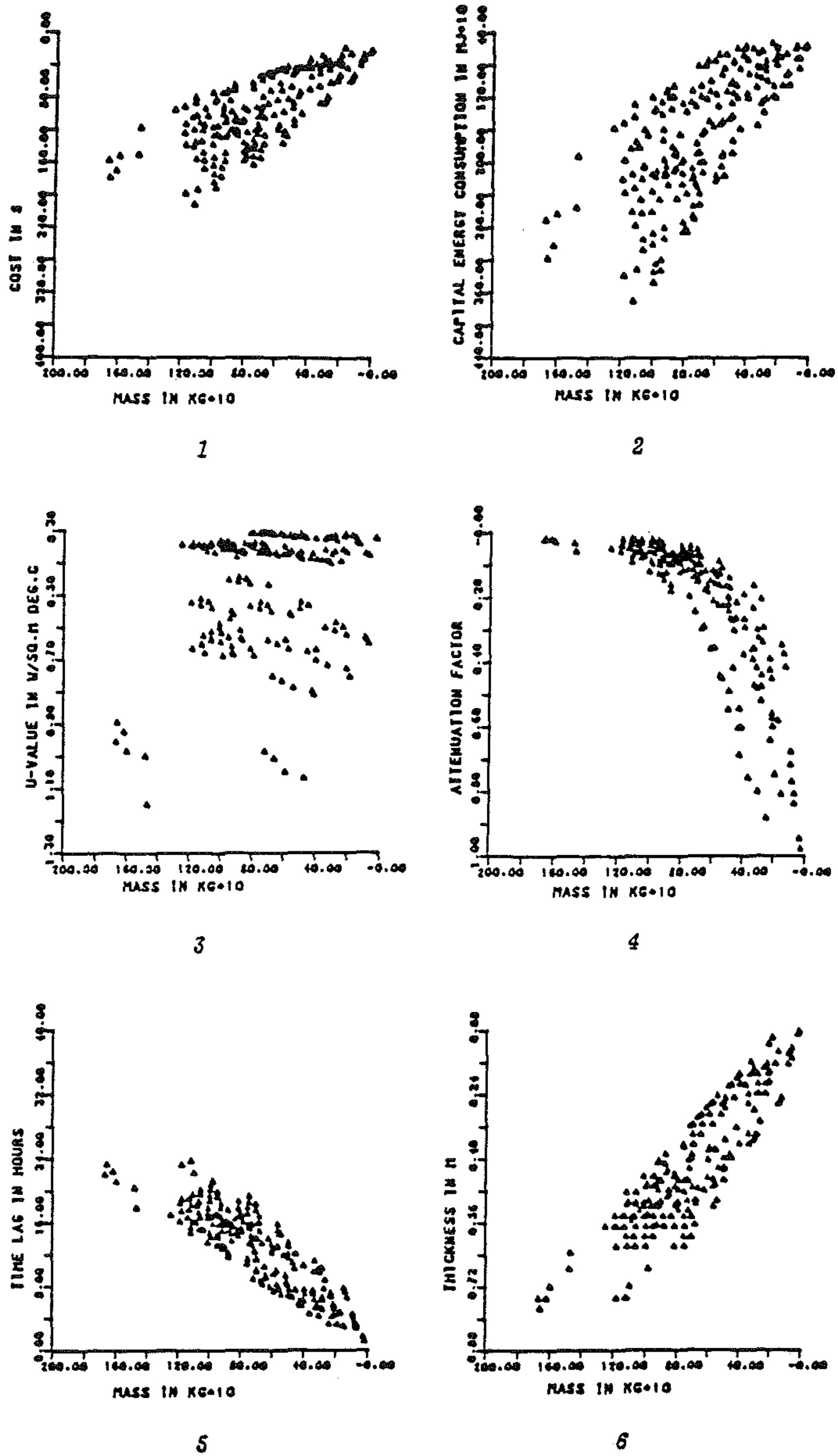


Figure 5. Pareto optimal solutions at level 1

	Mass	Cost	CEC	U-Val	Attn	Tlag	Thick
Mass		~	~	-	↓	↑	↑
Cost			↑	-	↓	↑	↑
CEC				-	↓	↑	↑
U-Val					-	-	-
Attn						↓	↓
Tlag							↑
Thick							

Symbol: ↑ , Linear relationship

Symbol: ↓ , Inverse relationship

Symbol: - , Independent

Symbol: ~ , Some relationship

Notations:

Mass	mass in Kg
Cost	cost in $
CEC	capital energy consumption in MJ
U-Val	thermal transmittance in W/sq m. deg.C
Attn	attenuation factor
Tlag	time lag in Hours
Thick	thickness in Meters

Figure 6. Performance interrelationship matrix

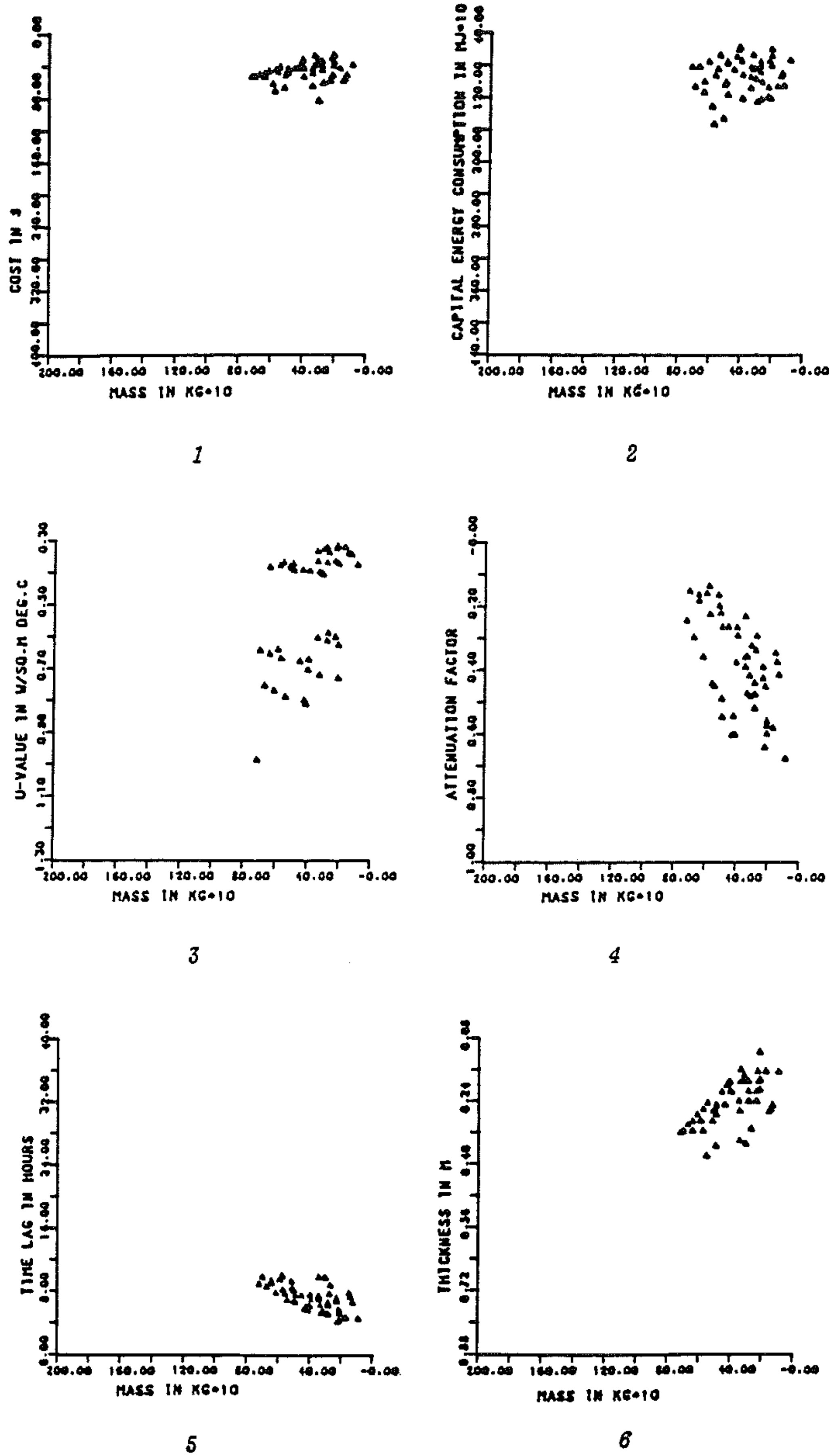


Figure 7. Solutions retained after setting inverse goals

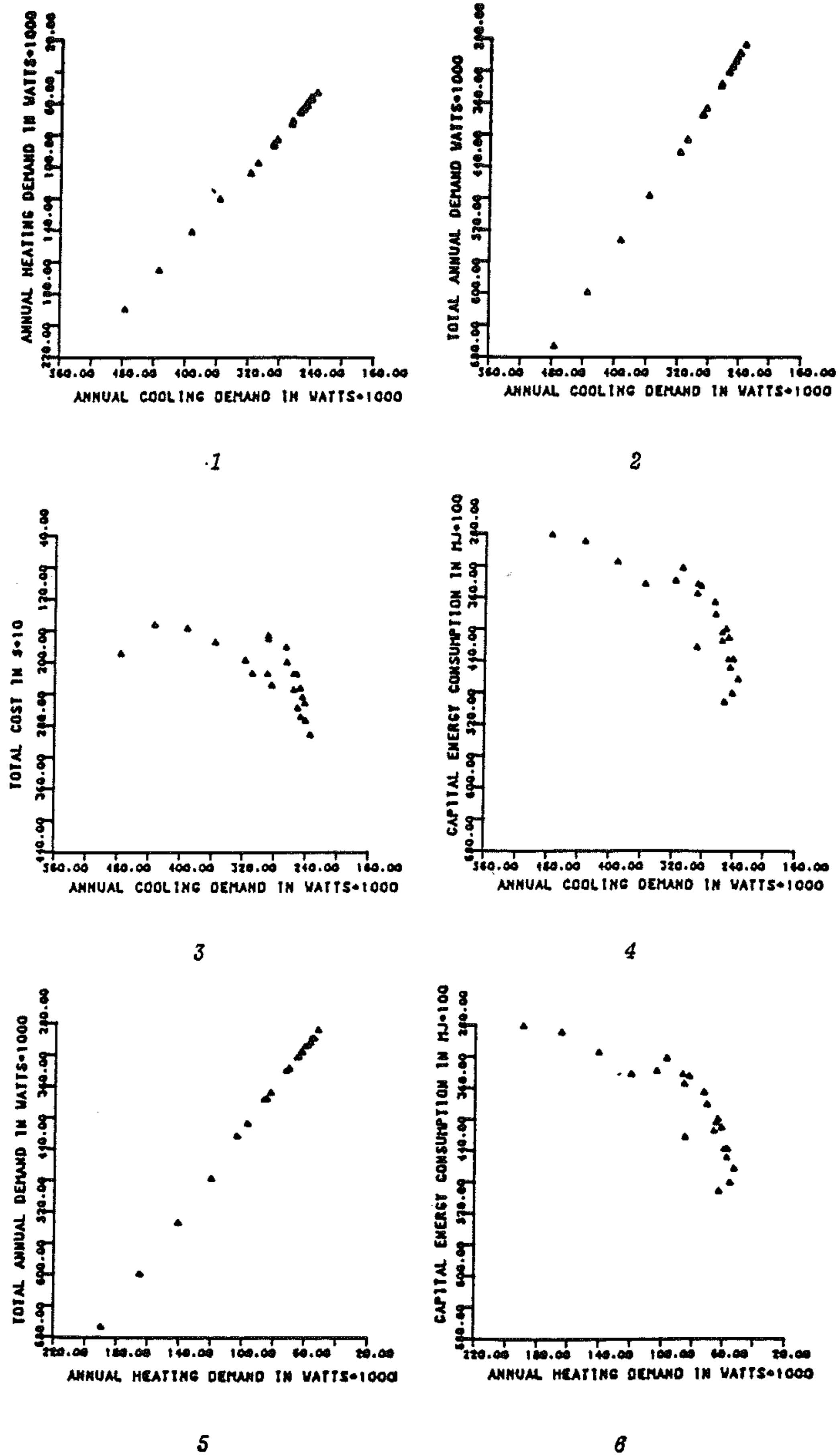
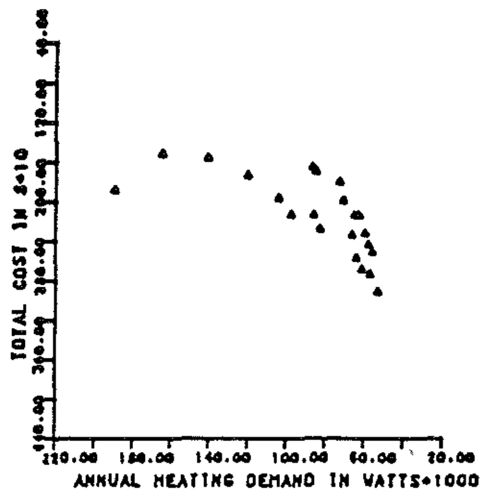


Figure 8. Pareto optimal solutions at level 2



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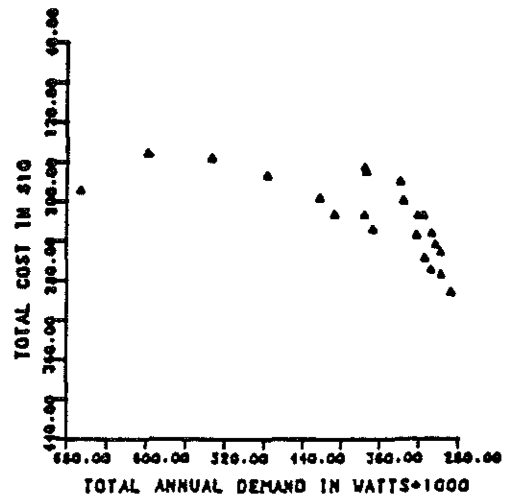

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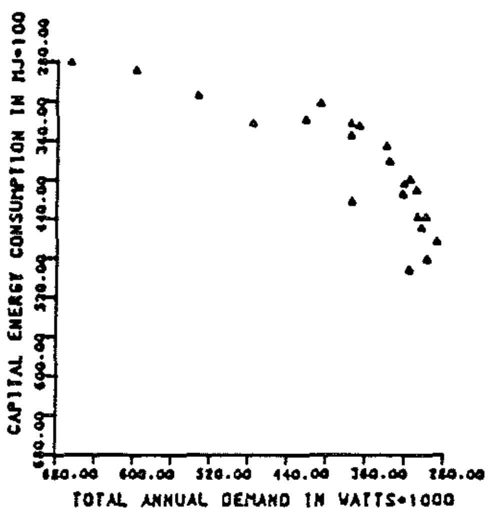

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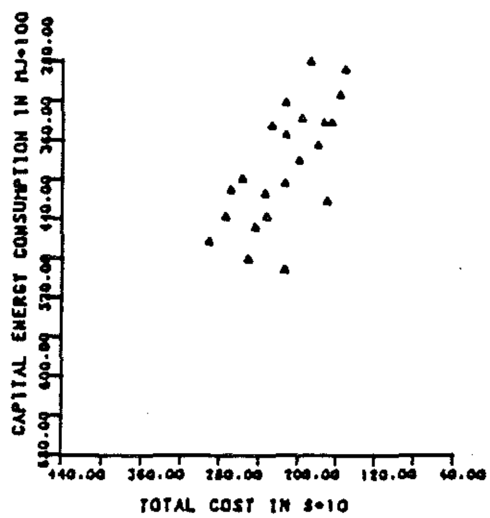

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Figure 8 continued