Energy in Context: A Multicriteria Model for Building Design

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A model is proposed for the representation and comparison of design alternatives which puts energy efficiency in a context of performances in other criteria. The model utilizes notions of decision and performance spaces and multicriteria Pareto optimization. A simple example is described.

1. ENERGY AND BUILDING

UNTIL the mid-1970s energy use was not a criterion of great importance in building design. Abundant low-cost sources of energy led to buildings which were totally dependent on mechanical systems for heating, cooling and ventilation. In consequence, energy requirements of buildings grew steadily year by year until it accounted for 23.5% of the energy used in Australia [1] and for over 40% in the United States [2]. The so-called 'energy crisis' has led to a much greater concern by building owners about the energy performance of building proposals and to the introduction of regulatory codes requiring minimum standards of energy-conservative design, usually by restricting the freedom of designers in choosing values for wall and roof insulation and glass proportions (for example, part FF of the England and Wales building regulations). At the same time, the availability of digital computers has made possible new methods of modelling heat flow and energy demand and the development of computer simulation programs which can provide more accurate predictions of the operational energy demand of a building design proposal than was previously possible. By repeating this simulation process the energy performances of alternative proposals can be compared. However, this new importance of energy demand as a criterion in building design is additional to and not replacing any pre-existing design criteria. Architects cannot design a building for energy efficiency alone; indeed, the most energy efficient solution is no building. The purpose of this paper is to put forward a model for the representation and comparison of design alternatives which places energy efficiency in a context of performances in other criteria. The uses of energy in building are for heating and cooling, lighting, transportation (lifts and escalators) and the operation of equipment related to the building's occupancy and function. Building design can influence all but the last of these uses, but in this paper we shall restrict the discussion to thermal performance.

2. DESIGN AND PERFORMANCE RELATIONSHIPS

The thermal performance of a building is dependent on the micro-meteorological conditions outside the building, the thermal behaviour of the building fabric and the comfort conditions required inside. The meteorological climate can be measured and to some extent predicted. Some measure of coarse control can be exercised in moderating its influence, for example, by planting and judicious choice of site. The prime factor, though, is the thermal behaviour of the building itself. The design variables that determine this thermal behaviour (for example shape, massing, enclosing materials and surface finishes) also influence performance in other criteria. Thus, in aiming to improve thermal performance an architect must consider the implications for other quantitative criteria such as capital cost and the usable area of the building, quite apart from his proper concern with qualitative aesthetic and social criteria.

2.1. Design → performance

For thermal design there is now a considerable number of computer simulation programs available. Some, such as DEROB [3] and ESP [4], require quite detailed descriptions of the building proposal and therefore cannot be used at the early stage of design unless numerous default assumptions are made. Others, such as those used in PACE [5] and SPEED [6], operate with simpler models
requiring much less input data and are aimed at providing indicative measures before the design has been fully worked out. PACE (Package for Architectural Computer Evaluation) originated in the late 1960s and even at that early stage responded to the multicriteria nature of building design by predicting the cost (capital and maintenance), spatial (plan and mass compactness), and activity (closeness of related departments of other functional components) performances of a design proposal as well as its environmental performance [5].

2.2 Performance → design

By repeating the simulation process with different values for the design variables, some indication of the best forms of design for desired performance can be inferred. In this way Oughton [7] showed how the energy consumption of a building is influenced by building form, orientation and envelope construction. Through the concept of thermally equivalent walls, Arumi [8] has shown the appropriateness of size of insulation for different climates. This performance → design relationship is also investigated by optimization formulations of the energy of thermal load problem, such as those by Gupta and Spencer [9], who minimize 'degree of discomfort' according to an objective function defined by Gupta [10]; Wilson and Templeman [11], who minimize the combined capital and operating costs of the heating plant and insulation; and Jurovics and Low [12] who minimize combined heating, lighting and cooling loads. There are many other examples in the literature. Almost all such optimization studies consider one criterion in isolation; in parallel with these studies of thermal performance, other researchers have been working on performance → design relationships for capital cost (e.g. Aguilar [13]) and planning efficiency (e.g. Eastman [14]).

2.3 Performance → performance

By performance → performance relationships we mean the implications of choosing a certain level of performance in one criterion on the performances that are then attainable in other criteria. The functional requirements of buildings and their components are often conflicting: at the whole building level the twin goals of maximizing area and minimizing cost frequently operate in conflict, and at the building component level a good example is provided by the twin goals of maximizing sound insulation (which is roughly proportional to mass) and minimizing mass for a partition. There is little published work exploring these conflicts and the tradeoffs necessary for their resolution in any explicit manner. Mattar et al. [15, 16] assess five performance characteristics for external walls (fire resistance rating, risk of condensation, thermal resistance, sound transmission and initial cost) and approach the performance tradeoff problem by articulating simple and partially-ordered preferences between the performance characteristics. Work at Sydney University (Radford and Gero [17, 18]; Gero and Radford [19]; Gero et al. [20]) has explored a more direct representation of tradeoffs through the presentation of Pareto-optimal sets of performances (see below) and developed a means through inverse goal programming (Gero et al. [20]) for choosing a 'best compromise' set of preferences between the performances.

2.4 Design → design

By design → design relationships we mean the implications of choosing a certain value for one design variable on the values that need to be given to other design variables if acceptable performance is to be maintained. Radford and Gero [18] derive 'environmental tradeoff diagrams' for daylighting and peak summer temperature in a room in a building, given a specific external environment and orientation. The diagrams show Pareto-optimal values (see below) for these performance measures and the associated values for a small set of design variables (glass type, wall type, window size and sun shade projection). By superimposing tradeoff diagrams with different restrictions on the design variables it is possible to trace design → design relationships. For example, the diagrams show how glass type and window size must be adjusted to keep peak summer temperature constant with least detriment to daylighting if sunshades are removed from a particular design proposal.

3. DECISION AND PERFORMANCE SPACES AND PARETO-OPTIMALITY

Before describing the formulation of a multicriteria model to explore the trade-offs between building thermal performance and other criteria, we shall briefly describe the notions of decision and performance spaces and Pareto-optimization which lie behind the work described in Sections 2.3 and 2.4 above.

In searching for a suitable design solution it is possible to delineate three representational aspects which may be used as vehicles in the description of decision making processes. These are: the decision space, the criteria space and the constraint set.

(i) The 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.

(ii) The criteria (or performance) space contains the description of all performances. The performance of a solution to a problem with M criteria can be represented as a point in M-dimensional space.

(iii) The constraint set contains the description of all restrictions which limit the range of decisions or performances.

Each point in the decision space has associated with it a point in the performance space and vice versa. The constraint set defines feasible regions in these spaces: constraints on decision, for example, have an explicit effect on the feasible region in the decision space and an implicit effect (through the decision/performance relationships) on the feasible region in the criteria space. In this model, the design problem can be described quite simply as the identification of the 'best feasible point' in the performance space and the corresponding point in the decision space. However, finding this 'best feasible point' is not always easy.

Taken alone, the performance space gives no clear indication of which solution is to be preferred: if we adopt the convention that increasing distance from the origin corresponds to increasing desirability then in Fig. 1, A is better than B in criterion 1 and B is better than A in criterion 2. Consider, though, the third 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 performances lie along a boundary of the performance space. They are known formally as the set of non-dominated, non-inferior or Pareto-optimal solutions (Fig. 2). Extending this concept to the general case of M criteria, a feasible solution to a multicriteria design problem is Pareto-optimal if there exists no other feasible solution which is better in at least one criterion and no worse in the others. For two criteria the Pareto set traces a curve along the edge of the criteria space. Higher dimensions are difficult to visualize but for M criteria the Pareto set will form a surface in M-dimensional space. For one criterion, on the other hand, the criteria space reduces to a vector and the Pareto set reduces to a point—the optimal solution in traditional single criterion optimization.

4. A MULTICRITERIA MODEL OF THERMAL PERFORMANCE, CAPITAL COST AND USEABLE AREA

The purpose of this model is to provide designers with prescriptive information on the relationships between thermal performance, capital cost and useable area for a building proposal before the building form is finalized. This is achieved by simultaneously considering the effect on these three criteria of systematic changes to the design variables. Initially, the form of buildings considered is rectangular parallelepiped shells with similar constructional properties throughout. The shape and massing of the building are varied through the aspect ratio (ratio of north to east walls) and the number of storeys. Orientation of the building (relationship of north facade to north), glass fractions and glass type complete the design variables.

The performance prediction models required are those that reflect the skeletal information available at the early stage of design while being responsive to the options available. For example, for thermal performance it is appropriate to calculate the building thermal load rather than its energy use, as the latter requires knowledge of the mechanical system characteristics. In this section we describe the selected thermal, cost and useable area models.

4.1. The thermal model

The thermal load within a building envelope is a result of:

(a) variation in climatic data such as outside air temperature and solar radiation;
(b) the heat gain/loss due to the thermal characteristics of the building envelope construction;
(c) the required inside conditions; and
(d) the internal heat gain, which is not considered at present.

4.1.1. Prediction method. Long-range values of outside air temperature for most locations follow a sinusoidal pattern. From tabulated data (Bureau of Meteorology [21]) an average pattern can be constructed for temperature variations over a design day in each month for a particular location. The intensity of direct solar radiation on all surfaces for the design day can be calculated by a formula which assumes sky conditions and an attenuated solar constant intensity. From these, the sol-air temperature on each exposed surface is calculated.

Building elements neither heat up nor cool down instantaneously and thus have some thermal inertia associated with them. This results in an attenuation and a time delay between cause and effect. When thermal inertia is considered the calculation is said to be dynamic. When thermal inertia is ignored the calculations are known as the static approximation [8]. Since the construction properties are not varied in this exercise, the static solution is used. The purpose here is to establish the relative thermal performance for different configurations of building rather than to predict individual performances with the greatest possible accuracy. Air infiltration is calculated by the air change method, assuming a fixed number of air changes occurring per hour in the space. The inside air temperature is assumed to be controlled by a thermostat setting which varies for cooling and heating periods and has temperature setbacks during periods of non-occupancy.

4.1.2. Thermal load ratios. March and Martin [22] have shown that for a simple rectangular block of given volume the built form which will minimize heat losses is one whose thermal image is a cube, i.e. the relationship of the sides is in...
the proportion of the average thermal transmittance of the opposite faces. Notationally this is

\[
x_1: x_2: x_3: u_1: u_2: u_3
\]

where \( x_1 \) is the length of building (m); \( x_2 \), width of building (m); \( x_3 \), height of building (m); \( u_1 \), average thermal transmittance of surfaces along the length (W/m² K); \( u_2 \), similar for width (W/m² K); \( u_3 \), average thermal transmittance of roof and floor (W/m² K).

For a given volume and thermal transmittance this 'optimum' building size can be determined, and hence the 'optimum' cooling, heating and total thermal load this will generate can also be determined. This can be used as a standard for comparing other building configurations. The calculated cooling, heating and total thermal loads are divided by the 'optimum' loads to yield thermal load ratios. These ratios, rather than the raw load figures, are used here as the criteria of thermal performance.

4.2. The capital cost model

All cost models are fundamentally based on an analysis of constructed buildings to establish an appropriate rate for a particular type of building (Ferry [23]). This base cost is adjusted to account for market conditions that affect current price levels. For this work, with thermal load the prime consideration, a cost model is required that reflects variations in shape, massing, window configurations, constructional properties and surface finishes. The technique currently used is the storey enclosure method [23]. The areas of the various floors are calculated and weighted by a factor of 2.0 for the ground floor, 2.15 for the first floor, 2.30 for the second floor, adding a factor of 0.15 for each additional floor above the ground floor. The weighted areas are summed and to this is added the area of the projection of the roof and the external walls. This total is the number of storey enclosure units in the building.

The cost of a constructed building divided by its storey enclosure units yields the cost per storey enclosure unit. The estimated cost of any other configuration of similar building type is then the product of its storey enclosure units multiplied by the cost per enclosure unit. To this cost is added the cost of staircases and mechanical services such as lifts. The total cost divided by the gross floor area is the cost per square metre of the building.

The number and size of staircases were calculated according to the requirements of the New South Wales, Australia, building regulations (N.S.W. Government [24]). The required number of lifts is predicted by a statistical model derived by Marmot and Gero [25]. The cost of these items were priced from Cordell's Building Cost Book [26].

4.3. The usable area model

The net usable area is calculated as a measure of utility of the building configuration. In this case, the net usable area is calculated to be the area inside the external walls less the area taken by services (lifts and staircases), with an allowance for circulation and toilet facilities. These allowances are as follows:

- **Circulation**: Ground floor 10% of net area, Upper floors 5% of net area
- **Toilets, etc.**: 5% of net area per floor
- **Staircases**: Based on the requirements of fire exits in New South Wales building regulations
- **Lifts**: Based on the statistical model of Marmot and Gero.

5. CASE STUDY: A BUILDING IN SYDNEY, AUSTRALIA

The case study considers a parallelopiped building in Sydney, Australia. The base data is:

- **Building volume**: 4000 m³
- **Minimum area per floor**: 800 m²
- **Storey height**: 2.7 m
- **Thermostat settings**: Heating 20°C, Cooling 25°C.

The design variables with their range of values are:

- **Aspect ratio**: 1, 2 or 3
- **Orientation**: 0°, 30° or 60°
- **Massing (number of storeys)**: 1, 2, 3, 4 or 5
- **Glazing fractions on each facade**: 0.4, 0.5 or 0.6
- **Glazing type (single pane)**: Clear, heat reflecting or heat absorbing
- **Shading**: None.

Making 405 possible design solutions. Rather than plot their performances in thermal load, capital cost and usable area directly in a three-dimensional criteria space we have plotted the projections of this space on its constituent two-dimensional faces.

5.1. The solution space

Figure 3 shows the complete set of performances. They group themselves into five bands, within which solutions have very similar capital cost and very similar usable area but widely differing thermal load ratios.

The prime purpose of this study is to examine the relationships between thermal load and these other criteria of cost and usable area. However, no clear pattern emerges. What we can say is that the range of values of thermal load ratio is smallest for single storey solutions and increases as the height of the building increases. What is clear, however, is that the design decisions have very much more proportional effect on the thermal load than on either capital cost or usable area. The lowest capital cost is about A$720/m², the highest is A$770/m², an improvement of about 6%. The highest usable area is 84%, the lowest is 74.6%, an improvement of about 13%. For thermal load, the lowest performance is a thermal load ratio of 1.2 while the highest is 6.7, representing an improvement of lowest over highest of about 80%. Although if we assess all these criteria in cost-benefit terms the potential variations in capital cost and usable area may be as important, or even more so, than those inthermal load, it is clearly worthwhile designing to minimize that load. This is especially so because Figs 3(a) and (b) show that there is little conflict between designing for minimum thermal load and either designing for minimum capital cost or designing for maximum usable area.

When we plot usable area against capital cost (Fig. 3c) each band collapses into groups of just three points. Tracing back to the design solutions we find that each group corresponds to a number of storeys and each point within a group corresponds to one of the three values of...
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aspect ratio. This collapse of the bands into points is, of course, a result of the prediction models used, which do not relate capital cost to glazing fraction or type. A more detailed cost model would spread these points into a neighbourhood. Single-storey solutions are most expensive but offer the largest usable area. Three storey solutions are cheapest while in between in order of increasing cost are the two-, four- and five-storey solutions, the relatively high cost of the latter two being due to the additional cost for lifts required in these solutions. For usable area, the lower the building the better since increasing the number of floors means increasing the area devoted to stairs and lifts.

5.2. Design → performance and performance → performance

The relative lack of conflict between thermal load and the other criteria is demonstrated if we carry out a Pareto-optimization over the three criteria. Of the 405 original solutions only 5 prove to be Pareto-optimal (Fig. 4) and these span a very small part of the total load ratio axis. Table 1 details the values of the design variables and criteria for these Pareto-optimal solutions.

The design → performance relationships are evident from the graphs. From Figs 4(a) and (b), the total load varies little whatever the choices about usable area and cost, as long as the choice of design is restricted to the Pareto set. From Fig. 4(c), improving usable area ratio means increasing cost. The two-storey solutions (Nos 2 and 3) appear to be a reasonable compromise.
Before we try different values for the design variables, it is worthwhile inverting the Pareto-optimization to find the very worst (instead of the best) solutions (Table 2). The configurations with the worst overall performance are those with the largest aspect ratio, oriented the maximum away from north, with clear glass windows of maximum size on all facades. The massing of the two buildings is very different, however, one being square and elongated while the other is narrow and high.

### 5.3. Design → design

To investigate design → design relationships we extend the range of values for the design variables, exploring orientations close to north and glazing fractions less than 0.4, 0.5 or 0.6.
Table 2. Pareto-optimal solutions (worst; orientation 0°, 30° or 60°, glass fraction 0.4, 0.5 or 0.6)

<table>
<thead>
<tr>
<th>Solution number</th>
<th>Orientation</th>
<th>Window fraction</th>
<th>Glass type</th>
<th>Aspect ratio</th>
<th>Number of storeys</th>
<th>Capital cost (A$/m²)</th>
<th>Useable area (%)</th>
<th>Total thermal load (ratio)</th>
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<td>1</td>
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<td>0.6</td>
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<td>84.01</td>
<td>4.15</td>
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<td>1</td>
<td>3</td>
<td>5</td>
<td>770.0</td>
<td>74.79</td>
<td>6.71</td>
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</tbody>
</table>

Table 3. Pareto-optimal solutions (orientation 0°, 5° or 10°, glass fraction 0.2, 0.3 or 0.4)

<table>
<thead>
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<th>Solution number</th>
<th>Orientation</th>
<th>Window fraction</th>
<th>Glass type</th>
<th>Aspect ratio</th>
<th>Number of storeys</th>
<th>Capital cost (A$/m²)</th>
<th>Useable area (%)</th>
<th>Total thermal load (ratio)</th>
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<tr>
<td>1</td>
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<td>0.2</td>
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<td>830.3</td>
<td>84.15</td>
<td>1.60</td>
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Fig. 5. The Pareto set of performances for the case study building with a modified range for orientation and glass fraction values.

REFERENCES

8. F. Arumi, Passive energy systems. Class Notes, School of Architecture, University of Texas, Austin (1981).


