A Theory of Architectural Design in which the Role of the Computer is Identified

T. W. MAVER*

To identify the role of the computer in architectural design, a model of the design activity is proposed which provides a framework for three basic types of process model—formal mathematical processes in which relationships are modelled, heuristic processes in which search rules are modelled and simulation processes in which solutions are modelled. Examples of each type are given and their usefulness discussed. A proposed line of development is described whereby those affected by design decisions can play a role in an iterative computer aided design procedure.

1. INTRODUCTION

ARCHITECTURE remains, from the entire range of areas of design endeavour, that profession which alone has failed to take full advantage of the digital computer. Among the factors inhibiting the realisation of the unfulfilled potential of the computer in building design, the lack of an externally valid model of the design activity which can serve as a framework for a taxonomy of computer design techniques and as a matrix for the correlation of research and development effort, is of paramount importance. Two other factors—the inability to support specialised disciplines in the numerous small practices, and the lack of inexpensive graphical interfaces to the computer—are clearly important but may be as much symptomatic as causal.

This paper sets out to provide a model of the existing relationship between the computer and the design activity on which to base a plan for the development of computer-aided architectural design.

2. A DESIGN PHILOSOPHY

Ackoff[1], in the context of planning, defines the ideal state as one in which every individual can obtain whatever he wants and in which he has a continuously expanding set of desires. The necessary and sufficient conditions for this state can be listed as:

(a) Politico-economic (PLENTY)—to provide every individual with instruments that are perfectly efficient for his objectives.

(b) Scientific (TRUTH)—to develop instruments and identify means which are perfectly efficient and to provide every individual with a knowledge and understanding of these.

(c) Ethico-moral (GOOD)—to remove conflict within individuals and between them, to provide peace of mind and peace among men.

(d) Aesthetic (REALITY)—to enable every individual to enlarge the range of his objectives through conceptualisation of new desirable states.

By definition an ideal state is that which is unobtainable and is approachable without limit. It is necessary, therefore, to define also a system of objectives (which are defined as ends which are attainable though not necessarily within the period planned for) which, if we are lucky, will give rise to a system of goals which are surely and predictably attainable.

For an objectives system one can take that developed by the BPRU and described by Markus[2]. The system comprises four subsystems—the building system, the environment system, the activity system and the objective system (figure 1). The overall objective can be stated as the optimisation of the return on the investment of the client’s resources, where resources investment is measured in terms of the cost of providing and maintaining a built environment and

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return is measured in terms of the activity performance indices.

The degree to which this objective is attainable, its compatibility to the system of ideals already stated and the extent to which it promotes definition of goals will emerge later in the paper. Suffice it to say at this stage that unless the decision as to whether or not an optimum allocation of resources has been achieved is taken in conjunction with those who will be affected by it, the philosophy will have been denied.

3. A MODEL OF THE DESIGN ACTIVITY

Modelling of the architectural design activity has become, over the last few years, a major occupation. It will continue to be a less than totally successful business while a single model attempts to combine the complexity of one man's concept of the activity with a desire for universal validity; this completeness/understandability conflict requires resolution in the modelling of any system.

The model used in this paper, which is that of Markus[3], is intended to be sufficiently simple to have external validity (figure 2). It comprises two dimensions: a design morphology comprising sequential stages from the strategic and general to the tactical and particular and a design process comprising iterative cycles between the steps of analysis, synthesis and appraisal. It is this model which will be used in a later section as a framework for a taxonomy of design process techniques; at this stage, however, it is necessary to give some attention to the capabilities and limitations of the computer.

Fig. 2. Model of the design activity.
4. THE CAPABILITIES AND LIMITATIONS OF A COMPUTING MACHINE

It has to be stated at the outset that the designers of computers are concerned not with an artifact which will emulate man, but with one which will complement him; it is less a matter of replacing man as of releasing his energies for the attainment of his creative aspirations. The complementary attributes of man and machine are summarised in what is known as the "Fitts List" (Table 1).

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Machine</th>
<th>Man</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed</td>
<td>Much superior</td>
<td>Lag 1 s</td>
</tr>
<tr>
<td>Power</td>
<td>Consistent at any level; large constant standard forces</td>
<td>2.0 hp for about 10 s; 0.5 hp for a few minutes; 0.2 hp for continuous work over a day</td>
</tr>
<tr>
<td>Consistency</td>
<td>Ideal for: routine repetition; precision</td>
<td>Not reliable: should be monitored by machine</td>
</tr>
<tr>
<td>Complex activities</td>
<td>Multi-channel</td>
<td>Single-channel</td>
</tr>
<tr>
<td>Memory</td>
<td>Best for literal reproduction and short term storage</td>
<td>Large store, multiple access. Better for principles and strategies</td>
</tr>
<tr>
<td>Reasoning</td>
<td>Good deductive</td>
<td>Good inductive</td>
</tr>
<tr>
<td>Computation</td>
<td>Fast, accurate</td>
<td>Slow, subject to error</td>
</tr>
<tr>
<td></td>
<td>Poor at error correction</td>
<td>Good at error correction</td>
</tr>
<tr>
<td>Input sensitivity</td>
<td>Some outside human senses, e.g. radio-activity</td>
<td>Wide energy range (10^{12}) and variety of stimuli dealt with by one unit; e.g. eye deals with relative location, movement and colour. Good at pattern detection. Can detect signals in high noise levels.</td>
</tr>
<tr>
<td></td>
<td>Can be designed to be insensitive to extraneous stimuli</td>
<td>Affected by heat, cold, noise and vibration (exceeding known limits)</td>
</tr>
<tr>
<td>Overload reliability</td>
<td>Sudden breakdown</td>
<td>&quot;Graceful degradation&quot;</td>
</tr>
<tr>
<td>Intelligence</td>
<td>None</td>
<td>Can deal with unpredictable and unpredictable; can anticipate</td>
</tr>
<tr>
<td>Manipulative abilities</td>
<td>Specific</td>
<td>Great versatility</td>
</tr>
</tbody>
</table>

Relating the attributes on this list to the steps in the design process, it is immediately apparent that the potential of the computer lies mainly in analysis and appraisal. This being so, the cyclic process of design will involve man-machine interaction and it is in the area of this interface that a great deal of hardware and software development is being concentrated. The advent of remote access time-sharing terminals which provide each user with what would appear to be exclusive use of a large machine, and the development of high level design orientated languages which are immediately understandable by the practitioner, are making effective man-machine dialogue economically feasible. A breakthrough in cathode-ray tube technology is imminent and will allow remote graphic communication with the computer to supplement or replace the present alpha-numeric method.

Although development continues on interfaces and on machines which will operate faster and have larger memories, the basic range of mathematical functions which the machine is capable of remains unaltered. All problems, therefore, must be dealt with in terms of these functions and the task of arranging this is the process of problem solving.

5. PROCESS MODELS

Figure 3 is the relationship, proposed by Coombs, Raiffa and Thrall[4], between the real world and representations of it. Since experimental design is less appropriate to architecture than it is to mass production industries, this section will develop, with examples, three categories of theoretical model which are sufficiently disparate to warrant separate study; these are formal mathematical models, heuristic models and simulation models.

5.1 Formal mathematical modelling

This can be defined as the modelling of the relationship between interdependent variables using mathematical expressions. A well known technique – linear programming—falls within this category. By definition linear programming is a technique whereby a linear objective function, subject to inequality constraints, is optimised. As an example, one can take the study of Krejčírov and Sipler[5], in which the linear objective function is given by:

$$\text{Cost}, C = 585x_1 + 1643x_2 + 816x_3 + 1747x_4$$
$$+ 436x_5 + 1771x_6$$

where $x_1, x_2, x_3$ etc. are the numbers of each of six different types of flats to be included in a residential development.
The linear constraints in this example were:

\[\begin{align*}
2x_1 + 2x_3 + 6x_5 + 2x_6 & \leq 58 \\
2x_1 + 8x_2 + 6x_3 + 8x_4 + 16x_6 & \leq 354 \\
10x_1 + 8x_2 + 10x_3 + 14x_5 + 16x_6 & \leq 466 \\
10x_1 + 30x_2 + 14x_3 + 24x_4 + 14x_5 + 34x_6 & \leq 1790 \\
12x_1 + 30x_2 + 16x_3 + 24x_4 + 14x_5 + 34x_6 & = 1820 \\
450x_1 + 1264x_2 + 628x_3 + 1344x_4 + 412x_5 + 1362x_6 & \geq 77,350 \\
-576x_1 + 144x_2 - 704x_3 + 176x_4 - 336x_5 + 192x_6 & \geq 0 \\
x_6 & \geq 8
\end{align*}\]

The minimum cost solution to this problem was calculated to be

\[x_1 = 11, \ x_2 = 36, \ x_3 = 5, \ x_4 = 21, \ x_5 = 2, \ x_6 = 0\]

In this example, the functional relationship between cost and the other design variables was known. In environmental design, however, the functional relationship between the dependent variable—cost in the example chosen—and the independent variables may yet have to be established. If this is the case, the technique is to hypothesise a relationship, say of the form

\[C = \alpha x_1 + \beta x_2 + \gamma x_3 + \delta x_4 + \mu x_5 + t x_6\]

and to gather sufficient data on the values of \(C, x_1, x_2, x_3, \ldots\) from previous solutions to allow the coefficients \(\alpha, \beta, \gamma, \ldots\) to be evaluated. The technique for this evaluation is known as regression analysis[6].

There are certain difficulties associated with this approach. In the first place one may, in order to simplify subsequent statistical analysis, hypothesise a relationship which is rather more simple-minded than that existing in the real world (e.g. an important variable may not have been accounted for, or the real relationship may not be linear, as assumed). Even where the hypothesised relationship can be statistically validated there is some danger in extrapolating from it for predictive purposes since the validation may hold only within the range of observed data. A third difficulty is that since the data used in the formulation of the relationship is drawn from previous solutions, the model is most unlikely to promote design innovation.

The reduction of a mass of probabilistic data drawn from a number of previous solutions into a simple equation does of course incur an accuracy penalty; at the strategic stages of design, however, where greater inaccuracy can be tolerated, the "weak laws" produced by the technique have their uses. Linear programming, on the other hand, used at a tactical level where relationships can be established by the laws of natural philosophy, is a fairly powerful tool.

Another formal mathematical technique which is enjoying vogue in building design at present is cluster or factor analysis used in the hierarchical decomposition and recomposition of sets and subsets of a large multivariate design problem[7, 8].

![Correlation Matrix](image)

In its simplest form the technique is one for which a matrix expressing the correlation between a set of variables \(A, B, C, \ldots\) (figure 4) is the input. The output is a number of subsets (figure 5)
formed either by maximising the internal integrity of the sub-sets or by minimising the links between the sub-sets. Provided the input data accurately expresses the relationship between each and every variable, the technique has value in structuring an otherwise unmanageable strategic problem.

5.2 Heuristic modelling

This process is carried out in situations where a "best" solution is sought from an effectively infinite range of possible solutions. The "heuristics" are simply the rules applied to limit the area of search to a manageable, but hopefully fruitful, sub-set of solutions. A well-known example of a search from a large number of solutions is route-finding in a maze; if the object is to arrive at the central and the subject chooses to start from a southern entrance, an appropriate "heuristic" may be to turn, in order of priority, north, west, east, south as opportunity is provided. (An almost identical problem relating to route finding in buildings, has been programmed by Beaumont[9].)

Fortunately, building design problems, unlike mazes, are not structured maliciously and there is some evidence that efficient heuristics can be applied in a number of cases.

As an example it is useful to take the work of Drummond, Paterson and Willoughby[10]. Given a number of buildings, the association between each of which is known (figure 6), it is required to place them on a site which has been partitioned to differentiate between suitable and unsuitable

\[
\begin{array}{cccccccc}
A & B & C & D & E & F & G & H \\
\text{arts} & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
\text{science} & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
\text{arts/science} & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
\text{education} & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
\text{residences} & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
\text{library} & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
\text{com.lecture space} & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
\text{administration} & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
\text{comm. facilities} & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
\end{array}
\]

Fig. 6. Association chart.

foundation conditions (figure 7). The number of possible solutions is exceedingly large (approximately \(3 \times 10^{18}\) for the placing of 10 elements on a 20 x 20 grid); the method adopted was to place manually one building in the best location on the site, place the next building such that the site value combined with the association between the two was maximised, place the third building such that the site value combined with the association between the third and the first two was maximised, etc. This technique necessitated a prior statement of a number of heuristics. One heuristic related to the order in which the buildings should be located: a decision had to be made to adopt the rule proposed by Whitehead and Eldars[11] (in which the building to be placed first is that having the highest association with all others; the order subsequently being proportional to the association of each unplaced building with all those already placed) or in reverse order of their future expansion requirements or according to some other rule.

Clearly the solution generated will depend on the heuristics adopted and since there is often no way of telling how appropriate the heuristics are, one cannot be at all sure how close (or far) the solution is from an optimum. In the example cited, an attempt was made to deal with two variables: association values and site values. Besides requiring an a priori decision as to the relative weighting of these two variables, the certainty as to the validity of the heuristics is lower than would be the case were only a single variable being considered. This is indicative of the fact that an attempt to deal with a multi-variate problem by heuristic modelling is fraught with difficulty: as the number of variables goes up, the heuristics and relative
weightings become more dubious until a stage is reached when the proximity of the solution to an optimum may be less than is achievable by purely intuitive methods.

For those who seek a further example, the work of Moučka[12] provides an interesting contrast to the example given in the field of layout planning by heuristic modelling.

5.3 Simulation modelling

For the purposes of this paper, simulation will be taken to mean the modelling of design solutions. Using the problem tackled by Drummond, Paterson and Willoughby as an example, simulation implies the inputting not only of an association matrix and a site plan but also a hypothesised design solution. The output is in terms of a “score” or performance index for association and for siting achieved by the hypothesised solution. By modelling a variety of solutions comparison of performance indices can be made and a “best” solution approached progressively. Since there is no requirement for an a priori statement of heuristics and weightings between variables, the number of variables incorporated in the model is not limited, cost, for instance, can be computed for every solution hypothesised.

An early and important simulation study, in which movement throughout a hospital building was simulated using a graphical input device is reported in “Planning for Hospitals: a Systems Approach using Computer-Aided Techniques (COPLANNER)”[13].

5.4 Relationship of process techniques to the design activity model

It should be clear from the foregoing that there is a strong correlation between the three types of process models and three of the steps in the design process. Formal mathematical models have their use mainly in ANALYSIS, heuristic models in SYNTHESIS and simulation models in APPRAISAL. The examples quoted can thus be plotted within the two dimensions of the design process as in Table 2:

<table>
<thead>
<tr>
<th>Strategic</th>
<th>Analysis</th>
<th>Synthesis</th>
<th>Appraisal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression analysis</td>
<td>Drummond et al.[10]</td>
<td>Drummond et al.[10]</td>
<td>Co-planner</td>
</tr>
<tr>
<td>Cluster analysis</td>
<td>Moučka[12]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Linear programming</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tactical</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2

Computer programs exist for all the examples quoted. Although categorisation of existing techniques has been suggested, the categories are not definitively exclusive, the heuristic program of Drummond, Paterson and Willoughby[10], for example, contains elements of appraisal and Co-planner requires some heuristics to effectively appraise movement in hospitals. It should be noted that the techniques can be used serially to considerable effect. Drummond et al., have used the output from their heuristic program as the input to a program which appraises the scheme on the basis of a large number of variables. An excellent example of all three techniques being utilised is provided by Beaumont[9]: a large set of spatial elements is decomposed by cluster analysis into sub-sets which are located, heuristically, on a grid; in turn each of these sub-sets is decomposed and the sub-sub-sets located; this process is continued until all the elements of the original set have been placed; at each stage of the decomposition, the level of those variables which were not considered heuristically are subjected to appraisal techniques.

An important distinction exists between computer techniques which are algorithmic and those which are interactive, i.e. between processes which are completely automatic from beginning to end and processes which require human intervention. Beaumont’s process is essentially algorithmic although he has made it possible to effect a manual interrupt to modify partial solutions prior to the next stage in processing. The price which has to be paid for algorithmic elegance is in terms of the machine’s inferior performance in pattern recognition and inductive logic.

6. A PROPOSED LINE OF DEVELOPMENT

Consideration of the foregoing indicates that while formal mathematical models and heuristic models have a use, this use is subject to fairly serious limitations. The confidence with which one can predict from regression equations based on past data is not high and the number of occasions where an objective function can be formulated without simplifying the problem to a level which contravenes realism are few. The task of devising and testing appropriate heuristics for the generation of multi-variate design solutions is difficult if not impossible and can lead inadvertently to poor solutions.

The proposed approach is based on the theory that if a number of variables are to be manipulated simultaneously it is not feasible to generate, explicitly, a design solution as effectively as an architect can intuitively; but that it is possible,
using an intuitive synthesis as a first approximation, to explicitly appraise it in such a way that promotes convergence by iterative modification towards an optimum solution. The iterative method of successive approximations is well tried in algebra and there would appear to be no fundamental reason why it should not apply to the simulation of design solutions. It does depend, however, on two conditions: one is that all possible solutions should exist along a single "objective" dimension of "good—bad", the other is that each appraisal should be carried out in sufficient detail to suggest the appropriate solution modification.

The mechanism proposed, for each stage of the design morphology, is one in which a suite of appraisal programs, covering cost and performance variables, would be applied to a solution hypothesised by the architect; the outcome of the appraisals would be considered by a "solution team" (as opposed to a design team) together with the non-quantifiable variables; if the balance between cost and performance or between different aspects of performance is not considered optimal, the solution would be modified and the process repeated (figure 8). The principle embodied is that of making the consequences of design decisions explicit to the "solution team" which can be composed of client, users, financiers, representatives of society at large, etc. To assist the solution team to negotiate an optimum solution through trade-offs and compromises, the norms, optima or statutory constraints for each variable can be provided as a basis of comparison for each variable performance index; the generation of an optimum for each variable independently can be achieved by the heuristic techniques already discussed.

In other design fields simulation has been recognised not only as a method of solving particular design problems but of providing the designer with a wealth of design experience in a short space of time. If cost and performance criteria are recorded for each of a large number of simulated solutions, the data can be used to generate the regression equation of the functional relationship between design variables. Thus the three steps in the design process come full cycle; the outcome of simulated appraisals becomes the input for formal mathematical analysis, as shown in Markus' paper "Design and Research"[14]. By this procedure, design by performance specification, rather than by investment specification as at present, may ultimately be possible.

Participation of those affected by design decisions in the process of reaching the decisions is an integral concept of the proposal. It must be clear to all designers that the layman's ability to make a relevant contribution to design is greater when he is responding to a proposed scheme than when he is asked, a priori, for a statement of needs; the approach outlined affords the former of these alternatives. The responses of the solution team to a variety of schemes can be formalised in a number of ways; one is to allocate to each participant a number of votes equal to the number of schemes under consideration.

The table shown (Table 3) may represent the voting after discussion has taken place. Since the object is to precipitate a coalition, the total vote is fed back to the participants and each given the

<table>
<thead>
<tr>
<th>Scheme</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>6</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>4</td>
<td>7</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>7</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>10</td>
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<td></td>
<td>4</td>
<td>3</td>
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<td>1</td>
<td>0</td>
<td>3</td>
<td>2</td>
<td>9</td>
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<td></td>
<td>5</td>
<td>4</td>
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<td>1</td>
<td>4</td>
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<td>7</td>
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<td>7</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td>49</td>
</tr>
</tbody>
</table>
opportunity to revote. This process may be con-
tinued until no change takes place between two
successive runs, indicating that all participants are
as satisfied with the total allocation of votes as is
possible. If one scheme emerges as the "best" only
it is carried forward to the next morphological
stage; if two, three or four schemes emerge as
approximately equally "best", all of these should be
carried forward. This game can be made more
sophisticated by allowing participants to withhold
all or some of their votes; then, if the total votes
cast is not equal, say, to half the total possible
votes, the design team must generate further alter-
atives to the existing schemes. Game theory
has developed little in the field of coalition, as
opposed to competitive games, but Flood[15]
describes some examples of a type similar to that
developed here.

The goals of a computer aided development plan
can now be stated as the production of a suite of
appraisal programs for each stage in the design
morphology. The goals are seen as making possible
the achievement of the design objective—a cost/
performance balance (figure 8) which optimises
the return on investment. As to the ideals, the
four necessary and sufficient conditions—a wealth
of alternative schemes, an understanding of how
they perform, an opportunity for the resolution of
conflicting needs and an opportunity to con-
ceptualise innovation—are, at least, not contra-
venered.

The challenge presented by the computer is
perhaps the most exciting one yet faced by the
profession. If we truly seek the ideal state, let's
get going on the goals!

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REFERENCES
1. R. L. ACKOFF, Lecture notes for course on Principles of Planning. University of Sussex,
8th-10th January (1969).
2. T. A. MARKUS, The role of building performance, measurement and appraisal in design
3. T. A. MARKUS, *ibid*.
4. C. H. COOMBE, H. RAFFTA and R. M. THIBAL, Some views on mathematical models and
5. M. KRIJČÍK and V. ŠÍPLER. Use of computers for determining the optimum develop-
ment pattern for a residential area, *Building Res. Stat. Library Commun.* No. 1235,
May (1965).
(1960).
8. M. MILNE, Architectural applications of computer based network analysis models,
9. M. BEAUMONT, Computer aided techniques for synthesis of layout and form with respect
10. G. DRUMMOND, W. PATTERSON and T. WILLCOUGHBY, Computer approach to built form
Science*, 1, 127 (1965).
12. J. MOLČIČKA, Decision making in the initial phase of design, *Architects' JI.*, to be
published.
14. T. A. MARKUS, Design and research: are they in conflict, unrelated or complimentary?
15. M. M. FLOOD, A preference experiment, Rand Corporation memo, Nov. 1951 (P-256),