CHAPTER 7

The impact of computer-based models on design decision-making

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THE CONCEPT OF COMPUTER-AIDED ARCHITECTURAL DESIGN (CAAD)

Design, the highest endeavour to which man can aspire, may be defined as
the activity of making explicit proposals for a change from some existing state
to some future state which more closely approximates to mankind's concept
of the ideal. As such, it embraces a wide spectrum of human endeavour; the
outcomes of the design activity are part and parcel of our everyday life and
are determinants, for better or worse, of our man-made future. In common
with all complex human functions the activity of design is ill understood: it
involves the most rational and systematic processes of human thought and
also the most intuitive conjectural leaps within the mind.

The central concern of design is the modelling of present and future reality;
the central concern of those engaged in the development of CAAD systems is
the construction of computer-based models which afford the designer insights
into the cost and performance characteristics of existing building stock and a
predictive capability as to the cost and performance characteristics of
proposed new buildings: Computer-based models have to be seen, then, as a
recent and dramatic extension of the plan and elevation which have been with
us for the last five thousand years; whereas the plan and elevation may be
thought of static and descriptive models, the new generation of computer-
based models are, by contrast, dynamic and predictive.

In the discussion of the relevance of computer-based models to the activity
of design, some notion of the disparate processes within the design activity is
helpful. Notwithstanding the current popularity of Popperian propaganda in
which ‘conjecture’ and ‘refutation’ loom large (Popper, 1961), the most useful
classification of the processes within design are those of Asimow (Asimow,
1962) viz. analysis, synthesis, appraisal. By analysis is meant the collection,
collation and correlation of the information relevant to the design problem;
by synthesis is meant the generation of formal solutions to the design
problem; and by appraisal is meant the testing of these solutions against the
explicit and implicit requirements of the brief.

It becomes quite clear when one compares the relative attributes of man
and machine (Singleton, 1966)—accepting that the computer has been
designed to complement rather than compete with man—that while
computers can make little or no contribution to the activity of synthesis, there
is a real prospect of an effective contribution to the analysis of design
problems and the appraisal of design solutions.

This chapter is devoted then to the exemplification of computer-aided
analysis and computer-aided appraisal within the design decision-making
activity. It does not concern itself with the application of computers to the
management of the design activity or to the automation of production
information. It is concerned with design decision-making rather than design
management; with the quality of the built environment rather than the
profitability of the office; with the satisfaction of the client rather than the ego
of the architect.

**ANALYSIS OF DESIGN PROBLEMS AND DESIGN SOLUTIONS**

Analysis in architectural design has been described as the collection, collation
and correlation of data relevant to the design problem; as such it informs and
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**Figure 1** Typical data matrix summarizing activities and their functional requirements
perhaps stimulates the generation of design solutions. The techniques proving
effective in architectural design have their origin in other fields of design
endeavour; this implies a commonality of design problem if not of design
solution amongst the range of design disciplines.

To exemplify the effective application of computers to analysis, three quite
different computer-based analyses will be described; the first two drafted in
from other disciplines, the third ‘home grown’. They are hierarchical
decomposition, linear programming and accommodation scheduling.

Hierarchical decomposition

Frequently the architect is faced with an embarrassing wealth of data relating
either to user requirements or to the characteristics of existing buildings. The
need is for an analysis which will distil this data into a form which provides
insight into the structure of the data set and thereby stimulate the generation
of design solutions.

For example, let us assume that the client can be prevailed upon to provide
information in numerical form on the functional requirements of each and
every activity which will take place within the building. Such information
might be set down in the form shown in Figure 1. The data given in such a
matrix can, by complex mathematical operations, be transformed into a
number of different visual representations. In effect, the mathematics
attempt to dimension the distance between each element in the matrix and
every other element. These distances can be expressed through the mathem-
atics of hierarchical decomposition in 2- or 3-dimensional Euclidean space
or in 4-, 5- or n-dimensional non-Euclidean space.

Taking, for example, the data given in Figure 1, the program MAGIC
(Bridges 1980) can collapse the data set into two dimensional space, either in
the form of a dendrogram, in Figure 2, or in the form of a cluster diagram, in
Figure 3, or in the form of a bubble diagram in Figure 4.

The dendrogram representation (Figure 2) shows the hierarchical structure
of the activities—individual activities coming together into groups and finally
going to make a complete whole; from this diagram the interlinking
connections of individual activities and groups of activities can be easily
identified. The nearer the ‘top’ the joining occurs the more closely associated
are the activities. The most obvious point in the interpretation of the
computer output—and not at all obvious in the original data set—is the
appearance of two distinct hierarchies.

Alternatively, MAGIC will separate out the data in the matrix of Figure 1
into groups or clusters of activities (Figure 3) rather than, in the case of the
dendrogram analysis, show their successive containment. Any number of
clusters may be requested; usually a maximum and minimum number of
clusters are specified and the program calculates the allocation of activities to
Figure 2  MAGIC: dendrogram showing organisational structure. The numbers refer to the activities defined in Figure 1.

Figure 3  MAGIC: nonhierarchic clusters analysis represented as bubble diagram. Three groups were identified and the size of the bubble indicates the cohesiveness of the group.
clusters for the extremes required and all the intermediate numbers of clusters as well. This is a useful facility when considering the disposition of activities to floors in buildings with fixed suitable areas. The program outputs the total areas required by each cluster and these areas may thus be matched against available space.

Yet another option within the program is for the transformation of the data into a bubble diagram (Figure 4). In this case each activity is represented by a bubble, drawn proportional in area to that required by the activity and with the distance between the centre of the bubbles inversely proportional to the magnitude of the association expressed in the original data matrix. Such a spatial representation can readily be used as the basis for a computer-based 'sketch-pad' such as that embodied in the program SPACES 2 (Th'ng and Davies, 1972).

The application of the hierarchical decomposition procedures embodied in MAGIC are not confined to the data implicit or explicit in a design brief. An obvious and valuable application of, for example, the clustering technique is to the BCIS information on the capital cost of buildings (Zachry, 1981): under development is a computer-based cost prediction technique which will analyse and cluster the BCIS data according to a set of design descriptors in such a way that any design proposal can be associated with that set of similar designs, drawn from the BCIS data bank, on which a capital cost prediction can accurately be based.

Linear programming

Planners are familiar with the problem of aggregating detailed population data to district and regional centres. The process, which is mathematically explicit but complex and is based on linear programming, has parallels in architecture.

Take, for example, the task of siting central facilities such as health centres, fire stations, schools, etc. within a region for which the population distribution is known. The problem is to site the given number of facilities and to allocate the population to each (Figure 5) in such a way as to minimize some agreed travel criterion (Figure 6).

In the case of health centres, the criterion may be minimization of total travel time whereas in the case of fire stations the (quite different) criterion may be to minimize maximum travel time. The analytical logic is further complicated by the requirement to constrain the size of any one facility in terms of the maximum and minimum population served.

The complex linear programming analysis which has to be carried out is handled by the program LOCAL—for Location/Allocation (Sussock, 1974). Figure 5 shows the hypothetical location/allocation of eight psychiatric day-care facilities in Aberdeenshire, based on minimization of total travel
time (Figure 6). It is interesting to note that by setting up a matrix of travel times between each and every population node, the program MAGIC will, in its bubble diagram mode, generate a ‘time-map’ of the area, thus allowing subjective location/allocation decisions to be made in comparison to those produced by LOCAL.

Linear programming, as might be surmised from the example of siting central facilities, is an analytical technique for the optimization of some objective function (e.g. the minimization of total travel time) subject to a set of constraints (an upper or lower limit on the size of any one facility). Such an analysis can be effectively applied to a wide range of architectural problems: the allocation of user activities to spaces within a building envelope, the routing of engineering services and the mix of house types within a proposed neighbourhood.

An interesting application of linear programming to the problem of optimum ‘mix’ is provided by a program INVEST (Maver et al., 1978). If the revenue and expenditure is known for each type of accommodation normally provided in a hotel (e.g. single bedrooms, double bedrooms, function suite, restaurant, grill, bar), INVEST will generate a schedule of accommodation which maximizes profitability, subject always to any declared constraints (e.g. fixed site area, the requirement to provide bedrooms for at least half the number of people attending a function, etc.).
Figure 5  LOCAL: population map of Aberdeenshire showing the location of 8 day-care psychiatric facilities as computed by LOCAL, together with the allocation of population to each facility.
Accommodation scheduling

In building types where the pattern of user activities changes rapidly over time, as for example in the operation of an educational timetable in secondary schools and colleges, the problem of establishing an efficient schedule of accommodation is acute. Some indication of the problem is given by gathering data from an existing school and comparing, on the same graph, the activity pattern and the existing schedule of accommodation. The technique for representing these data on the same graph (Maver, 1979) is illustrated for a secondary school in Figure 7: the activity pattern is plotted as the cumulative number of period over which each class size meets; by dividing the
Figure 7  ECOLE 1: activity pattern graph for part of a comprehensive school.
The existing accommodation and an 'optimum' schedule have been constructed on the same diagram.

cumulative number of periods by the number of periods in a weekly cycle of the timetable, a horizontal scale of 'number of rooms' is produced, allowing the existing schedule of accommodation to be plotted.

The striking characteristic of Figure 7 is the degree of mismatch between the accommodation provided and the pattern of user activity. The 100 per cent over-provision, by no means atypical in post-war schools, is due partly to the fact that there are too many rooms, and partly to the fact that the majority of rooms are oversized. A more efficient match for the activity pattern is provided by the 'optimum schedule' in which a range of new sizes are identified.

The computer program ECOLE 1 (Davies and Th'ng, 1975) has been developed to allow architects and educationalists to co-operate in matching accommodation schedules to alternative curricula, student rolls, teaching methods and operating policies. Input to the programs consists of subject names, space types (lab., classroom, etc.), curricula and space per student. For any suggested year or subject grouping, the program will prepare the activity pattern and fit an 'optimum' range of spaces to it. The program output takes the form of a schedule of accommodation for each subject or group of subjects, together with statistics on spatial utilization.

The opportunity is provided in the program to establish the degree of physical flexibility necessary to change from the schedule of accommodation
appropriate to some current educational regime to the schedule appropriate to any proposed future regime.

The few examples of computer-aided analysis given above are a small fraction of the growing repertoire of techniques being developed to collect, collate and correlate data relevant to architecture design problems. Though widely different, one from the other, they all are mathematical abstractions, or models, of reality: none is concerned with the form of buildings. The next two sections deal, explicitly, with computer-aided appraisal of building form.

APPRAISAL OF WHOLE BUILDING DESIGN

Appraisal is that process within the design activity concerned with the testing of design hypotheses. In computer-aided appraisal, the testing is done on a computer-based model of the hypothesised design; in effect the model allows a prediction to be made of the quantitative and qualitative attributes which will characterize the real building. The process of computer-aided appraisal is as represented in Figure 8.

The designer, following an analysis of the problem (using, perhaps, techniques similar to those described earlier) generates a design hypothesis; this hypothesis—essentially the proposed form and fabric of the building—is input to the computer program. The program models the behaviour and characteristics of the building, as if it existed in reality and outputs predictions as to the cost (capital and recurring), performance (spatial, functional,
environmental) and visual quality of the design. The designer, in his/her evaluation of the output profile, modifies the design hypothesis. The iterative process continues until the designer is satisfied that the balance within the profile, and between the profile and the more qualitative output, is optimum.

Clearly, if the process is to promote design decision-making which leads to improved quality in the built environment, the information profile provided by the output must guide the designer towards those design modifications which bring about significant improvement in some aspects of cost and/or performance without significant deterioration in the others. Initially, degree of improvement or deterioration might have to be judged against arbitrarily set upper or lower limits of cost and performance. As an increasing number of design alternatives are explored, however, insights are provided into the complex relationships which translate unit change in one variable into corresponding changes in all other variables (Figure 9). As these insights develop, the validity of pre-set criteria (e.g. 2 per cent daylight factor, U-value of not more than 0.6) becomes increasingly suspect; what emerges as important is the rate of change of any one variable to all others and the concept of a 'balance' which is approached dynamically.

![Diagram](image)

**Figure 9** A representation of the complex interaction between cost and performance variables
Obviously, then, computer-based appraisal models should be comprehensive and integrated. Those involved in their development and use have become increasingly aware of how a modest design change (particularly to geometry) dramatically affects the entire range of cost and performance variables. It follows then that computer-aided appraisal should be applied at the earliest possible stage in design when the architect makes the important formal decisions which are the determinants of so many of the quantitative and qualitative attributes of the building.

It should be made clear, at this point, that the decision as to what profile of cost and performance is optimum remains a matter of subjective value judgement. The thrust of the argument for CAAD is that, as in a court of law, subjective value judgement should be made on the basis of the most complete, most explicit and most neutral evidence available.

GOAL: General Outline Appraisal of Layouts

GOAL (Sussock, 1978) is one example of a computer-based appraisal model relevant to the early stages of building design. The intention is that it should be easy for the designer to input his/her design hypothesis, that the range of cost and performance predictions should be comprehensive and understandable, that it should be readily accessible and inexpensive to use and that it should be as applicable to the redesign of existing buildings as it is to the design of new buildings.

The designer can represent the geometry of his design hypothesis to GOAL in a variety of ways: by typing in the co-ordinates, by digitizing a sketch on a tablet or by drawing on the screen of a computer graphics terminal. The geometry, input floor by floor, is shown on the screen and can be manipulated using a cross-wire cursor in conjunction with a command menu (Figure 10). The program allows a number of views to be obtained: floor plans, axonometrics (Figure 11), sections (Figure 12) and, in conjunction with the program BIBLE (Parkins, 1979) perspectives (Figure 13). As soon as the scheme is input to the computer, a summary of areas can be obtained (Figure 14).

The designer now specifies the desired construction by choosing from a variety of constructional components. The program stores the unit cost and thermal properties of the constructional components within a number of constructional types. As wall and roof components are selected the designer also specifies the percentage glazing required. With construction specified and summarized (Figure 15), the program can output environmental information regarding rates of winter heat loss (Figure 16) or summer heat gain, together with an analysis of energy loss and gain due to insolation, conduction, ventilation, occupancy and lighting.
Figure 10  GOAL: floor plan being manipulated on the computer screen

Figure 11  GOAL: axonometric view generated by the program
Figure 12 GOAL: sectional view generated by the program

Figure 13 GOAL: perspective view generated by the program in conjunction with BIBLE

Figure 14 GOAL: tabulation of functional areas output by the program
### CONSTRUCTION DATA

**ELEMENT**  | **SURF. TYPE** | **AREA [M²]** | **%GLAZ**
--- | --- | --- | ---
**GEOMETRY**: HOTEL DESIGN | **GEOMETRY**: HOTEL CONSTRUCTION I
1 | 1 | RESTAURANT | 1.2 | 24.0 | 0.0 | 0.0
| 1 | 3 | 1.0 | 13.5 | 60.1 | 1.0
| 1 | 4 | 0.5 | 40.5 | 60.1 | 1.0
| 1 | 2 | RESTAURANT | 1.2 | 39.0 | 0.0 | 0.0
| 2 | 1 | LOUNGE | 1.2 | 15.0 | 0.0 | 0.0
| 3 | 2 | 3.5 | 29.5 | 50.1 | 1.0
| 2 | 1 | 3.4 | 34.5 | 50.1 | 1.0
| 3 | 2 | KITCHEN | 1.2 | 18.0 | 20.1 | 1.0
| 3 | 1 | 4.4 | 9.0 | 0.0 | 0.0
| 3 | 2 | 1.1 | 15.0 | 0.0 | 1.0
| 3 | 2 | KITCHEN | 1.2 | 9.0 | 20.1 | 1.0
| 3 | 1 | 1.0 | 9.0 | 0.0 | 0.0
| 4 | 1 | FOYER | 0.9 | 33.0 | 70.1 | 1.0
| 4 | 1 | 0.9 | 15.0 | 70.1 | 1.0
| 4 | 2 | FOYER | 0.9 | 15.0 | 70.1 | 1.0
| 4 | 3 | FOYER | 0.9 | 24.8 | 0.0 | 1.0
| 5 | 1 | ADMINISTR' | 2.2 | 51.0 | 50.1 | 1.0
| 6 | 1 | 2.2 | 39.0 | 50.1 | 1.0
| 6 | 1 | STEAKBAR | 2.2 | 48.5 | 50.1 | 1.0
| 6 | 1 | 2.2 | 27.0 | 50.1 | 1.0

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**Figure 15** GOAL: tabulation of constructional choices made by the designer

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**ENVIRONMENT**: WALL HEAT LOSS: WINTER

**GEOMETRY**: HOTEL DESIGN | **GEOMETRY**: HOTEL CONSTRUCTION I
**CONSTRUCTION**: HOTEL SITE: GLASGOW

**BUILDING ORIENTATION**: 0 DEG

**COMPONENT**  | **WALL** | **M²** | **AREA** | **KW**
--- | --- | --- | --- | ---
5 | 1 | ADMINISTR' NORTH | 57 | 51.0 | 2.3
7 | 1 | FUNCTIONS NORTH | 57 | 54.0 | 3.1
1 | 1 | RESTAURANT WEST | 51 | 40.5 | 2.1
8 | 1 | BEDROOMS NORTH | 50 | 48.0 | 3.4
8 | 2 | BEDROOMS NORTH | 50 | 48.0 | 8.4
2 | 1 | LOUNGE WEST | 47 | 34.5 | 1.6
6 | 1 | STEAKBAR EAST | 47 | 21.0 | 1.0
6 | 2 | STEAKBAR EAST | 47 | 24.0 | 1.1
7 | 1 | FUNCTIONS EAST | 47 | 42.0 | 2.0
3 | 1 | KITCHEN NORTH | 34 | 15.0 | 0.6
3 | 2 | KITCHEN NORTH | 34 | 9.0 | 0.3
1 | 1 | RESTAURANT NORTH | 26 | 24.0 | 0.6
2 | 1 | LOUNGE EAST | 26 | 15.0 | 0.4
5 | 1 | ADMINISTR' EAST | 26 | 30.0 | 0.6
6 | 1 | STEAKBAR WEST | 26 | 15.0 | 0.4
7 | 1 | FUNCTIONS WEST | 26 | 33.0 | 0.9
8 | 1 | BEDROOMS EAST | 26 | 40.5 | 1.0
8 | 2 | BEDROOMS WEST | 26 | 40.5 | 1.0
8 | 2 | BEDROOMS WEST | 26 | 40.5 | 1.0

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**Figure 16** GOAL: tabulation of rates of winter heat loss output by the program
Figure 17  GOAL: summary and detailed costs output by the program

Capital and running costs are output in summary and detailed forms (Figure 17).
Following each section of output, the program offers the designer the opportunity to change his design hypothesis (Figure 18). By this means a very large number of design alternatives and design developments can be explicitly explored in a very short period of time.

Use of GOAL

The program GOAL has been used in a wide range of professional and educational contexts. The case study which is summarized below typifies the iterative search which a designer is capable of making with such a powerful
tool: first an exploration of geometrical forms followed by an exploration of constractional alternatives.

The design brief in this case study was a thirty-eight bedroom hotel to be situated on the sea front of a small Scottish town (Maver and Wong, 1981). The schedule of accommodation has been developed by means of the program INVEST (Maver et al. 1978); consequently a set of target costs and a target profitability were explicit from the outset.

Figure 19 presents a summary of the four formal layouts explored by the designer. For each layout, GOAL provided, amongst other things, data on the wall-to-floor ratio, volume compactness, annual energy consumption, artificial and natural lighting, satisfaction of the energy regulations, running and capital costs and the all important matter of profitability. These cost and performance characteristics have been compared by the designer in Figure 19.

At this stage in the development of the design, the designer made the subjective value judgement, based on the profiles of Figure 19, that geometry 4 offered the greatest potential. The second phase of the appraisal involved comparative evaluation of constructional systems as applied to scheme 4. Figure 20 provides the designer's summary of the search: firstly, three wall types were tested, then two levels of glazing, both single and double-glazed.

The information in the bottom right-hand corner of Figure 20 is significant; it summarises the constructional choice made by the designer. Instead of accepting the set of design decisions which indicated maximum profitability, based on the client's proposed tariff structure, the designer has proposed a marginally more expensive building but has been able, on the basis of the information provided by the program, to specify what change in the tariff structure would be necessary, in such a building, to achieve the client's target profitability.

Clearly then, the explicit information provided by the program promotes an informed value judgement. This judgement will have been influenced, and rightly so, as much by the perspective sketches (Figure 21) based on the output of the BIBLE program as by the designers rigorous approach to the appraisal of design alternatives and their impact on profitability.
APPRAISAL OF BUILDING SUB-SYSTEMS

The concept of integrated and comprehensive appraisal of whole buildings at an early stage in design, has been exemplified by GOAL. GOAL includes a number of appraisal routines, each of which addresses a specific sub-system within building design. The intention of this section is to show how any one of these sub-systems might itself be the focus of a computer-based model. The concept, then, is one of 'nested' models: a general model may be thought of as comprising a series of more specific models each in turn itself comprising a series of yet more specific models. As we step down one level in the hierarchy of models, generality and comprehensiveness is given up in favour of detail and rigour.

At one level 'below' GOAL, computer-based models for the appraisal of three sub-systems will be described:

AIR-Q — for the modelling of movement within buildings
ESP — for the modelling of the dynamic energy behaviour of buildings
BIBLE — for the modelling of the visual impact of buildings

Taken together they show that CAAD techniques are as relevant to the aesthetic attributes of buildings as they are to those attributes which centre on the quantifiable laws of physics, time and economics.

AIR-Q: A Model of Movement within Buildings

Within terminal buildings, the dynamic flow of people through the various activities, processing areas and waiting areas, can be represented as a two-dimensional network in which each node represents an activity (performed by or on a person) and the links between nodes represent the possible directions of movement. For example, Figure 22 shows how this might be used to describe the sub-set of activities associated with international passenger arrivals and departures in an air terminal.

Networks of this type can be built-up and amalgamated to form larger networks more representative of the whole building system. Also, individual nodes might be further split (or 'reduced') to give a more detailed description of component parts. Obviously, the amount of detailed description or generalization in the activity network will depend on the purpose for which it is intended.

The problems of congestion and prolonged queueing in airports generally arise out of and are aggravated by the fluctuations in throughput flow which occur over time. In order to understand fully the behaviour of the terminal system, it is therefore necessary to simulate the variations in input/output...
Figure 19  Four alternative hotel geometries compared in terms of a range of cost and performance variables, generated using the program GOAL.
THE IMPACT OF COMPUTER-BASED MODELS

WALL TO FLOOR RATIO

VOLUME COMPACTNESS

ANNUAL ENERGY CONSUMPTION

% ARTIFICIAL LIGHTING

% NATURAL LIGHTING

SATISFIES REGS. FF4

RUNNING COST

CAPITAL COST

PROFIT

IN DESIGN — AN HOTEL

Appraisal
Figure 20  A number of alternative construction choices compared in terms of costs, predicted by the program GOAL
GLAZING TYPES

1. SINGLE GLAZING
2. DOUBLES GLAZING

SELECTED SYSTEM

WALL TYPE: DOUBLE BRICK + CAVITY + INSULATION

* GLAZING: STANDARD 4% WITH APPROPRIATE EXCEPTIONS
* ROOF TYPE: HIGH INSULATION
* ROOF LIGHT 0% WITH APPROPRIATE EXCEPTIONS

IN DESIGN — AN HOTEL
Figure 21  A number of perspective views of the final hotel design, based on output from the program BIBLE
flows according to the anticipated schedule of airside and landside movements.

Input to AIR–Q (Laing, 1975) consists of:

(a) a representation of the network in terms of nodes and links, drawn on the screen of the computer terminal (Figure 23);
(b) serving times (input as probabilistic frequency distribution statistics) and nodal splits on the route links;
(c) arrival and departure schedules and throughput figures.

In effect, AIR-Q simply simulates the behaviour of the system by advancing an internal clock, while keeping track of the history of the status of
the system in terms of passenger populations at each time increment. The status of the system at each point is written to a file which may be interrogated by the program user.

It is thus possible for the user to request output on the population at any individual node or set of nodes over any period within the duration of the simulation (Figure 24). In response to the output the designer may elect to increase or decrease the provision of servers (e.g. at check-in, baggage reclaim, customs, etc.) or to investigate the behaviour of the system under stressful conditions (e.g. fog, strikes, introduction of 'jumbos', etc.).

In order to validate the predictive accuracy of AIR-Q, records were kept of the behaviour of Glasgow Airport during its peak holiday operation. It was thus possible to compare the actual status—recorded numerically and on video-tape—with the predicted values. The level of agreement between predicted and actual performance was surprisingly high.

Although initially intended as a tool for airport designers, the logic and techniques embodied in AIR-Q are equally applicable to any building or part of a building which is intended for the dynamic processing of people or materials. Thus, AIR-Q has to date been applied to the simulation of the following non-airport activities:

(a) a rail terminus—a very large complex system incorporating main-line passengers, three underground lines, bus terminus, car and taxi movements;
(b) a canteen servery—whereby a number of alternative strategies and spatial configurations were investigated for relative efficiency;
(c) a shipyard—in which the elements being processed were steel plates and sections, moving through a system of cutting machines and assembly processes;
(d) evacuation of a building on fire—an alternative approach to compliance with the building regulations.

In the application to evacuation of a building during fire it was possible to simulate the outbreak of fire at various points in the building under different sets of building usage patterns.

**ESP: A Model of Energy Flow in Buildings**

The thermal simulation model, ESP (Environmental Systems Performance) (Clarke 1979), is based on an implicit numerical technique, which is unconditionally stable for all computational time-increments, and operates in conjunction with hourly values of various climatological parameters. In general the formulation of an implicit numerical method is essentially a three-stage procedure.
Figure 23  AIR-Q: the network of activity within the airport is drawn on the computer screen and forms part of the input to the program

Figure 24  AIR-Q: population distribution output by the program for a chosen set of activities over a chosen period of time
(a) Nodes are placed at preselected points of interest throughout the system to be simulated.
(b) For each node in turn and in terms of all surrounding nodes which are in thermal contact, the governing differential equation is replaced by an implicit numerical approximation. This is repeated at the beginning of each time-step throughout the simulation.
(c) The resulting set of equations (one for each node) are solved simultaneously at each time-step.

The ESP model takes account of the transient conduction through all multilayered constructions. In addition to this, the model incorporates considerations of:

(a) the internal long-wave radiation exchange between enclosure surfaces;
(b) the casual gains from occupants, lights, machinery, etc.;
(c) the effects of short-wave radiation impinging on exposed external and internal surfaces;
(d) the shading of external opaque and transparent surfaces and the insolation of internal surfaces;
(e) the effects of natural ventilation and infiltration;
(f) the strategy of operation of the installed plant;
(g) the prevailing wind speed and direction.

In essence the thermal simulation program allows the designer to assess and appraise alternative thermal design and operational strategies by permitting the imposition of selected conditions and restrictions, with respect to time, on plant and/or environmental parameters within the enclosure. The simultaneous solution of the complete implicit difference equation-set representing the enclosure thermal exchanges over some period is considerably complicated by this essential interaction (the equation-set must be computed anew at each time-increment) and, as a result, solution by straightforward matrix inversion techniques involves an inappropriate effort. The actual solution method employed is based on a proprietary matrix inversion technique which has proved to be efficient and inexpensive to use.

The input to ESP consists of a representation of the geometry and construction of the proposed design. Output includes graphs of any chosen environmental parameters (Figure 25) and of temperature variations across multi-layered constructions (Figure 26).

An opportunity has been found to validate the predictive qualities of ESP against the actual behaviour of monitored buildings. Two houses (one occupied, one unoccupied) in Livingstone New Town were extensively monitored using thermocouples connected to a chart recorder. The monitoring equipment allowed records to be kept of the internal environment and
Figure 25  ESP: graph of the relationship between internal temperature and two climatic variables over a chosen twenty-four hour period

Figure 26  ESP: graph of the temperature variation through a multi-layer roof structure over a chosen twenty-four hour period
energy consumption of the houses under varying (and recorded) climatic conditions. To date, the results relating to internal environmental conditions have been analysed. In general, a very good agreement was obtained in terms of both absolute values as well as the characteristic shape (response), with the discrepancy between the value predicted by ESP and the monitored values in most cases falling within the error range associated with the monitored data (Figure 27).

As pressure grows from Government and client bodies the building design professions will be required to take increasing account of the energy behaviour of buildings. Already the program ESP is in great demand for a range of design and re-design problems, including the following.

(a) Investigation of the best way to treat the facade of a large dockland complex to make it suitable for housing departments of a polytechnic.
The re-design problem was complicated by the fact that, owing to the massive construction, the introduction of lighting and people was likely to cause extremely large heat gains; solutions to the problems were constrained due to the fact that a preservation order existed on the building. Use of ESP allowed a suitable economic solution to be found.

(b) Upgrading existing housing stock. Many government agencies in UK own housing dating from the early 1950s. As these fall due for upgrading the intention is to introduce higher insulation standards and other design modifications. ESP has been used by a private architectural practice to help establish the most cost-beneficial upgrading strategy: a sample of houses in any estate are appraised using ESP, firstly in their original state and subsequently with a range of alternative upgrading strategies. In this way the architect can ensure best use of the clients investment.
(c) Design of critical environments. ESP has been used to good effect by a central government design agency facing the problem of designing an astronomical laboratory. In such a laboratory control of the thermal environment is crucial to the effective working of the telemetry equipment.

(d) Testing of new design solutions. In large building complexes there may be advantage in incorporating innovative design solutions for the conservation of energy. ESP has been effectively used in such a case by a large multi-disciplinary design practice which wished to employ a solar wall in a multi-million pound building complex for a leading computer company.

Figure 28 BIBLE: input to BIBLE is possible by specification of points on any two of the three views of the building—in this case a ship factory
BIBLE: A Model of the Visual Impact of Buildings

BIBLE (Building with Invisible Back Lines Eliminated) (Parkina, 1979) is a program for producing views of building with (optionally) hidden lines removed. No originality is claimed for the algorithm but a degree of acceptance in practice has been obtained by careful design of the user interface.

The input (Figure 28) and user interface (Figure 29) of BIBLE are designed to be as easy for the inexperienced user as possible, without sacrificing the capability to specify arbitrary projections. This is achieved by four features.

(a) Fail-safe design: any invalid or wrong input produces an English-language error message apologising for the program's inability to understand the input provided and explaining what sort of input was expected or what options were available to the user at that point.

Figure 29  BIBLE: the menu of commands, plan and default values which allow ready specification of viewing parameters
(b) Graphic specification of view point. This allows the user to point on a displayed plan view to a place in the vicinity of the building, and in effect, ask ‘What does it look like from here?’

(c) Use of default parameters: all the view control parameters have default values computed by the program for each data set as it is read in. Thus it is possible simply to read the data file and immediately call for a view, and get a meaningful picture.

(d) A command menu on the screen gives the user a visible reminder of what he can do without verbose prompts, and more detailed information can be obtained by selecting the ?HELP command.

The full list of user-specifiable view parameters and default values is as follows:

(a) The EYE POINT from which the scene is viewed may be any point \((X,Y,Z)\), provided it is outside the region containing objects. \(X\) and \(Y\) may be specified graphically. The default is ‘a long way away’ in \(-X-Y+Z\).

(b) The FOCUS POINT which is the other end of the line of sight may be any point \((X,Y,Z)\). \(X\) and \(Y\) may be specified graphically. The default is the middle of the scene. The focus point may be moved in order to obtain two-point perspectives or views of off-centre parts of the scene.

(c) The MID-POINT (of the resulting picture) may be any point \((X,Y,Z)\). \(X\) and \(Y\) may be specified graphically. The default is the middle of the scene. The mid-point is normally set the same as the focus point, but it may need to be different for two-point perspectives or non-orthogonal parallel projections.

Hidden lines may be removed (which is the default), drawn dashed, or left in.

The output device may be a Tektronix display, or a plotter with the picture scaled to A1, A2, A3 or A4 size. Output device selection is dynamic and may be changed between pictures.

Options for picture size control are:

(a) fill screen or plotter paper, leaving 10 per cent margin (default);
(b) user-specified viewcone angle between 0 and 175 degrees;
(c) photomontage mode—user specifies focal length (default 35 mm) of a camera placed at the eye point and pointing towards the focus point, and the enlargement factor (default 1.0—i.e. contact print) from the negative to the print, and the program scales the output so that it fits in the correct place on the print.
The projection used may be perspective (by default) or orthogonal.

BIBLE has been successfully used to visualize both the outside and the inside of buildings. Figure 30 shows one of the series of views of a proposed ship factory; Figure 31 provides a check on the site lines from any specified seat to the stage of what might have become the new Edinburgh Opera House.

Two approaches to relating the building to its site are possible. Figure 32 illustrates how BIBLE can be used to generate not only the proposed building—in this case the Hilton Hotel which will occupy the site in Edinburgh originally intended for the new Opera House—but also the existing townscape, including the famous Lyceum Theatre, as viewed from Edinburgh Castle. Alternatively, at the expense of viewpoint flexibility, but with savings in data preparation and computing time, it is possible, using the photomontage facilities of the program, to generate a perspective view which is correctly scaled and framed for superimposition on a site photograph (Figure 33), in this case of a proposed industrial museum.

The photomontage option within the program greatly facilitates program validation; one simply photographs an existing building, inputs its geometry to the program, specifies the camera position, lens focal length and print
Figure 31  BIBLE: a perspective view from behind the topmost gallery within the once proposed Edinburgh Opera House
Figure 32  BIBLE: a perspective view of the proposed Hilton Hotel and of the existing Edinburgh townscape adjacent to the site
enlargement factor. The resulting view can then be overlayed on the photograph for comparison purposes.

The question of whether the site should be computer modelled or photographed is an interesting one. As suggested already, to enjoy complete flexibility of viewpoint, it is necessary to model the site within the computer, as in the application illustrated in Figure 32. The choice of data preparation in such circumstances may be relieved by recourse to photogrammetric techniques whereby pairs of stereo photographs are used to generate data on existing buildings (Figure 34).

Such an approach is wholly inappropriate in rural settings. However, in these circumstances photomontage is obviously the approach to be adopted. The question is, particularly in cases such as the routing of electricity pylons, from where should photographs be taken? This question is largely answered by recourse to the suite of computer programs known as VIEW (Aylward & Turnbull, 1977) which analyses ordnance survey data in order to establish the
THE IMPACT OF COMPUTER-BASED MODELS

Figure 34 The use of photogrammetric techniques to aid in the construction of photomontage perspectives

Figure 35 The use of VIEW to determine appropriate viewing points for the construction of colour montages using video facilities

degree of visibility of proposed construction over a wide area of the rural landscape (Figure 35).

Development in computer hardware and software for visualization is very rapid. BIBLE will shortly be replaced by VISTA (Visual Impact Study Technical Aid) (Fox, 1981) which generates highly convincing prospective views which are coloured, textured and lit. Programs such as VISTA herald a new era in CAAD.

IMPLICATIONS FOR PRACTICE AND EDUCATION

When one considers that modelling techniques in architectural design have not changed significantly in five thousand years—i.e. since plan and elevations were first used—then it becomes obvious that the introduction of a whole new generation of computer-based models will have a dramatic impact on architectural practice and architectural education. The impact will stem from the fact that the new generation of models, as opposed to paper-based plans and elevations, are predictive rather than descriptive, dynamic rather than static, explicit rather than implicit. This section attempts to anticipate the nature and extent of these impacts by reference to the examples in the three previous sections.
Implications for practice

Figure 8 represented the designers iterative search for a solution in which an appropriate balance is struck within the range of cost and performance criteria. The quality of the outcome of the search procedure will depend on two things: the appropriateness of the starting point (i.e. the initial design hypothesis) and the relevance of the cost/performance measures output by the appraisal method. Use of analysis techniques such as MAGIC SPACES 2 and INVEST provide the architect with an explicit rather than an arbitrary starting hypothesis based on rigorous and testable logic. Thereafter, programs such as GOAL help guide the architect by providing explicit measures of predicted cost and performance. In practice, access to such appraisal techniques is known to increase the search coverage by ten fold (Kernohan et al., 1977): not only is the search coverage extended, it is also much more purposefully directed, with the architect able to compare the quality of any one solution against the quality of all previous solutions.

Design team working:

A great deal of design time is lost as design hypotheses are passed to and fro between the architect and specialist members of the design team. Quite frequently the scheme on which the architect has lavished time and effort is found by one or other of the specialists to be infeasible. With access to explicit appraisal techniques it is possible to check a wide range of criteria simultaneously from the outset of the design activity. Moreover, it is entirely practicable for each member of the design team to have access to, and operate on, the common design model whether or not they share a design office. The models, then, provide a strong integrating force in design team working.

Design insights:

Apart from the use of appraisal programs in the search for an optimal solution to a particular design brief, the programs can be used in a ‘research and development’ context to provide insights into how design decisions affect cost and performance attributes (Bridges 1976). Typically, the designer would select an existing building as the vehicle for his study then, keeping all other design variables constant, systematically vary one design factor while recording the cost/performance output from the program. In this manner the architect can establish sets of causal relationships which provide powerful insights into the design activity.

Objective and subjective judgements:

Contrary to the fears of many architectural practitioners, the use of CAAD
techniques focusses increased attention on subjective value judgements, rather than less. As the measurable attributes of design alternatives are made more explicit, the necessary value judgements are forced to the surface of the design activity and, thereby, themselves become more explicit.

General: if CAAD techniques such as those described in this chapter are to be developed to their full potential, it will necessitate a diversion of professional effort away from the design of individual buildings in favour of a commitment to designing better design methods and models.

Implications for education

Students currently in schools of architecture will be at the peak of their careers around the year 2000. The pressure on the schools to provide an education and training which will stand the student in good stead between now and then is considerable. In an increasing number of departments of architecture and building science, importance is being placed on the concept of modelling: i.e. the development and use of models of the operational behaviour and aesthetic character of design proposals which will allow prediction of how real buildings will perform in the real world.

Co-operative effort is already being made by a small number of European schools to base student design project work on a number of the computer programs described in this chapter notably GOAL and BIBLE.

It is anticipated that undergraduate, postgraduate, and mid-career education opportunities in CAAD will expand rapidly during the 1980s.

Implications for building users

There is growing evidence of dissatisfaction on the part of the users of buildings. Two inter-related reasons for this dissatisfaction can be advanced:

(a) the lack of a reliable communications interface between the user and the architect which might make user need less liable to misinterpretation;
(b) the embodiment in the design solution of subjective value judgements which are essentially those of the architect rather than those of the users.

Recognition of the problem has led increasing numbers of (usually young) architects to involve themselves more intimately with the user community in an effort to more fully and more accurately interpret user needs and values. This approach represents an attempt to bring the interface between architect and user to an earlier point in time and to blur and de-formalize the communication process.
An alternative, and largely unexplored, approach is to postpone the user/architect interface by allowing the user community to penetrate deeply into the design activity to the point where needs and values are made explicit in spatial terms.

It is suggested that computer models make this alternative approach not only feasible but preferable to the 'barefoot architect' approach. The characteristics of computer-based appraisal models which are relevant to this claim are as follows:

(a) the models are, in effect, learning aids which promote the rapid development of insights into the way in which design decisions effect cost/performance attributes;

(b) the cost/performance profile resulting from the final user-generated design hypothesis provides an explicit performance specification—embodying the user's value judgements—on which the executive architect can sensibly operate.

The suite of programs known as PARTIAL (Aish, 1977) allows user participation in design to be studied. The participant uses the graphic manipulation commands to select, place and shape the rooms, walls, doors, windows, and partitions. The participant visually reads his drawing on the screen. In a corresponding way the computer 'reads' the drawing by making a numeric description of the design as a data file.

The participant can evaluate his design according to his own criteria as an experienced user, by using subjective visual and spatial information from the plan. The computer, on the other hand, can evaluate his design with objective measures of performance such as indices of capital cost, energy cost, day-lighting and planning efficiency. These measures are displayed to the participant in a simplified but unambiguous manner (Figure 36).

Using the graphic manipulation commands the participant can modify the design. He or she can add, shape, reposition or remove the rooms and the cladding elements. The computer redraws the modified design and always presents to the participant a tidy and accurate representation of the current design. The computer can also re-evaluate the design after such a modification so that the participant can see if he has improved both the objective as well as the subjective qualities of his solution. The participant can continue the iterative process of modification and evaluation until a design evolves with what he considers to be the appropriate mixture of subjective qualities and objective properties.

The major conclusions and implications which emerge from an experiment (Hirst and Watts, 1979) in which nursery school headteachers were given the opportunity, individually and in groups, to design an 80-place nursery school, are as follows.
Figure 36 PARTIAL: a nursery school layout generated, with the aid of the program by a nursery school teacher

(a) Nursery school headteachers are capable of formulating design objectives and producing layout schemes for 80-place nursery schools which are considered to incorporate successfully the majority of their initial design objectives. These designs are considered by the participants themselves to be more acceptable than comparable architect-produced designs.

(b) Participants evaluate their own individual design more highly than other participants' individual designs. However, they are capable of cooperating to produce a collective nursery school design which is not only an improvement in building performance and space allocation terms upon the design from which it evolves, but is also evaluated more highly than the participants' individual designs.
Figure 37  Computer technology and telecommunication technology linked to promote participation in design and planning decisions
Figure 38 A scenario for 'experiential appraisal' of the acoustic environment in a concert hall

(c) Further support for the feasibility of this type of involvement comes from the finding that not only do architects evaluate the participants' designs as highly as those of architects, but also they considered the group solutions to be an improvement over the individual solutions upon which they are based.

THE FUTURE

Earlier in this chapter a parallel was drawn between the genesis, some five thousand years ago, of architectural drawings and the genesis, ten years ago, of CAAD. Whereas architectural plans and elevations, as models, have developed very little over fifty centuries, the development of computer-based models, if we can extrapolate from events over the last decade, promises to be
rapid and dramatic. (Maver, 1976). With advances in telecommunications (cable TV, etc.) and in computer technology (microprocessors, raster-scan colour terminals etc.) it is possible to anticipate developments in at least two important directions:

(a) greater involvement in design decision-making by those people who are affected by design decisions (Figure 37);
(b) a move towards models which allow 'experiential appraisal' of the qualities of the built environment, e.g. acoustic quality (Figure 38).

It is most important that the architectural profession, with its deep commitment to and systemic view of the quality of the built environment should face up to and accept the challenge of CAAD.

REFERENCES