Chapter 8

COMPUTER AIDED DESIGN: APPLICATIONS IN ARCHITECTURE

Tom Maver

Contents

1.0 Design Concepts
2.0 Sub-System Design
   2.1 The Process Sub-System
   2.2 The Energy Sub-System
3.0 Total System Design
   3.1 The Form and Content of PHASE
   3.2 Observations on PHASE
4.0 Conclusion

1.0 Design Concepts

Design is the activity of making explicit proposals for a change from some existing state to some future state which more closely approximates to a 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 human-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 and conjectural leaps within the mind.

The design professions are many and varied; they include the engineering professions—mechanical, civil, electrical, electronic, aeronautical, nuclear, naval architecture, chemical, environmental—the architecture profession and the industrial design profession. The educational systems from which these professionals emerge, and the institutes of which they are members are unique, disparate and, sadly, often competitive. Design then, unlike medicine, has no unifying educational or professional corpus; the Design
Research Society is a modest but important force in identifying the intellectual core of the design discipline and as the impact of the outcomes of design decision-making impinges more and more on our daily lives it is likely that the educational implications will be more responsively recognized.

More than anything else the application of the computer to design is drawing together the endeavours of designers from a host of professional spheres. Central to the activity of Computer Aided Design (CAD) is the concept of developing, within the computer, a model of the operational behaviour of the proposed artifact. The behavioural model can be thought of as a system: the system inputs are in effect the design hypotheses and the system outputs are predictions of the performance characteristics of the design under a particular set of context variables (Figure 1).

This systems view of design recognizes that the activity of design decision-making is not wholly contained within the technological sphere but may well have implications—functional, economic, social and aesthetic—for society at large. Successful computer applications to limited technical problems abound, of course: it is very useful to input to the computer a set of beam loadings and to have it output a minimum depth of beam. The pressing problems facing society today—ecological pollution, dwindling
energy and material resources, urban deprivation, etc.—demand a more systemic view of design; a view that will recognize the aspirations and value judgements of all those who will be affected by the design decisions.

The development of systemic computer-based design models is in its infancy but advancing rapidly in most fields of design endeavour. Nowhere more so than in the field of architecture, building science and urban planning. In the course of designing a building the architect is concerned to satisfy, as best he/she can, a wide range of disparate and sometimes conflicting objectives: the building must be structurally sound, environmentally comfortable, efficient for its purpose, aesthetically pleasing and economical to acquire and run. The brief the architect is given is unlikely to be explicit as to the acceptable level of any of these criteria (except perhaps to impose an upper limit on capital cost). The architect engages, then, in an iterative, open ended, multi-variate search process during which the directions of search and the final outcome depend in large measure on implicit and subjective value judgements.

The philosophy underlying the current generation of Computer Aided Architectural Design (CAAD) models is not one of simplifying the problem in order to make it uni-variate and free of subjective value judgement; rather it is one of recognizing the complexity of the problem—the fact that it is multi-variate (and multi-person)—and of providing as rich an information base as possible about the predicted performance of the hypothesised solution on which explicit value judgements can be justifiably made.

Developing the systems model of Figure 1, the CAD activity can be represented as in Figure 2. The designer generates a design hypothesis
which is input into the computer (representation); the computer software models the behaviour of the hypothesised design and outputs measures of cost and performance on a number of relevant criteria (measurement); the designer (perhaps in conjunction with the client body) exercises his/her (or their) value judgement (evaluation) and decides on appropriate changes to the design hypothesis (modification).

Representation. As subsequent examples will illustrate, the representation of the design hypothesis will be required to take a form appropriate to the appraisal measures which the software is designed to carry out. The representation may be simply alpha-numeric, or increasingly commonly, topographic (e.g., a building plan, a bridge elevation, a printed circuit layout, a mechanical linkage, etc.); it is the interface between the designer’s mental model and the computer based model and, as such, is the focus of the human-machine exchange.

Measurement. The software model of the behavioural characteristics of the design artifact which exists within the computer must be capable of interpreting the input representation and of applying known algorithms which model aspects of the design’s character and behaviour. The output measures of cost and performance may be wholly descriptive (e.g., building plan area, maximum bridge span, number of circuit nodes, lengths of linkage arms, etc.), wholly predictive (e.g., the capital cost of the plan layout, the deflection profile of the bridge span, the resistance between two circuit nodes, the angular velocity of a linkage arm, etc.) or an appropriate mix of descriptive and predictive measures. Additionally, it may be advantageous to have the software effect a visual transformation on the input representation, to output additional views of the design hypothesis (e.g., a 3-D perspective of the building plan or bridge).

Evaluation. The profile of the cost and performance characteristics which are output by the computer—supplemented by perspective or other views—form the information base on which the designer acts. Evaluation of a profile of measures on disparate and possibly conflicting criteria can be undertaken only by the application of value judgements relating to the perceived needs of the client/user body and of society at large. The introduction of CAD models does not obviate the need for evaluative decisions; indeed, by making the information base explicit, CAD models throw into sharp focus the subjective aspects of the design decision-making activity. In some instances, the brief for the design problem may express upper and lower limits of acceptability for some or all of the cost/performance characteristics, against which the profile may be judged. Increasingly, however, it is recognized that such a priori constraints cannot be set sensibly in ignorance of the causal
inter-relationships between the elements of the cost/performance profile: for example, the requirement to achieve a minimum of 2% daylight factor in a school plan may result in an unacceptably high energy cost for heating. In effect, if a priori cost/performance specification is a meaningful concept, agreement on its form is likely only to emerge from extensive and controlled explorations using the CAD model.

Modification. Any design hypothesis embodies a unique set of design variables. For example, a particular plan layout has a particular floor area, shape of envelope, topological relation of spaces, etc. Each design variable contributes, to a greater or lesser extent, to the behaviour of the design as a whole and hence to the cost/performance profile. If, from the evaluation of the profile it is considered that, for example, the level of daylighting in some rooms is unacceptably low, the designer must decide in respect to which design variable the overall design hypothesis must be modified. Improvement in this aspect of performance may be achieved by modification of any one of several design variables; moreover, a change in any particular design variable is likely to affect not only daylighting but many (if not all) of the other cost/performance characteristics. The nature of the causal relationships between each and every design variable and each and every cost/performance variable is not, unfortunately, known a priori, but must emerge in the process of iterative use of the CAD model.

It will be seen, then, that if the representation and measurement modules of the design system can be set up and made available, the processes of evaluation and modification take place dynamically within the design activity as determinants of, and in response to, the pattern of explorative search. This mode of working puts a premium on ease of communication with the computer: current developments are divided roughly equally between bureaux offering remote multi-access to a large processor and in-house dedicated mini-computers.

The claim has been made that the systems view of design developed thus far has applicability to most fields of design endeavour—from the design of a gearbox to the design of a nuclear power station. The evidence needed to justify the claim is more voluminous than could be contained within a single chapter in a book of this type. Instead, the intention is to exemplify, from a single profession—architecture—the application of CAD to a range of problems relating to sub-systems within buildings and to the problem of the systemic design of the building as a whole.

2.0 Sub-System Design

A building can be thought of as comprising a number of interconnected sub-systems—structure, construction, plant and services, etc.—each of
which is sufficiently complex to warrant a specific CAD model. In this section two models will be discussed:

- The operation of the facilities within a building in relation to the processing of people and/or materials (the process sub-system) and
- The operation of the fabric of the building in relation to environmental control and energy consumption (the energy sub-system).

2.1 The Process Sub-System

In a significant number of building types—notably transport termini—the processing of large numbers of people is crucial to the functioning of the building. In an airport, for example, the designer is concerned to incorporate an adequate and economical provision of facilities (check-in desks, ticket desks, baggage reclaim carousels, etc.) to satisfy the demand which will be made on the building. In systems terms, the design problem is as shown in Figure 3.

Representation. In the computer program AIR-Q (Laing, 1975) the designer represents a design hypothesis to the computer by constructing the network of passenger movement on the computer screen, accompanied by suggested levels of facility provision. This mode of representation can be explained by reference to Figure 4.

For each type of process, the designer causes a symbol to be drawn on the computer screen as follows:

- Activity Node: e.g., check-in, bank, customs. Associated with each activity node the designer inputs a 'number of servers' and parameters which give the distribution of 'serving time'.
Trigger Input Node: e.g., scheduled bus arrival, scheduled plane arrival. Associated with each trigger input node is an arrival time and passenger complement.

Non-Trigger Input Node: e.g., sporadic car arrivals. Associated with each non-trigger input node are the parameters which give the distribution (perhaps random) of such arrivals.

The symbols are connected on the screen by means of directional links, as follows:

- Open Link: e.g., uncontrolled flow of passengers. Associated with each open link is the proportion of passengers taking this route.
- Trigger Link: e.g., controlled flow of passengers. Associated with each trigger link is the scheduling time of the 'call' for passengers and the numbers of passengers involved.

Measurement. The program models the operation of the air terminal by painstakingly advancing the set of processes by a succession of small time increments. Typically, the time interval chosen might be four minutes. In the first time step, a bus may have arrived and the passengers may have been processed through check-in; meantime, a scheduled aircraft arrival may have taken place. And so on. The program measures and records in a file, the status of the system at each time increment; measures consist of queue sizes, throughput times, idle server times, etc..

Evaluation. A tableau of synoptic output can be obtained from the program: which provides, for each facility, the average passenger 'stay time', the maximum and minimum population at that facility and the time at which the maximum and minimum populations occurred within the whole period simulated. This tableau guides the designer to look in more detail at critical aspects of the system. For example, the variation in population over any chosen time period (in any degree of temporal detail) within any group of facilities can be displayed (see Figure 5).

Even in a CAD model which focuses specifically on a particular building sub-system—in this case movement of airport passengers—there is no obvious single optimizing measure of performance. The designer (perhaps in conjunction with the client) has to consider, evaluatively, the trade-offs between, for example, extra provision (e.g., more check-in desks) and smaller queue sizes.

The evaluation problem is exacerbated by the fact that the system operates stochastically. The time taken to sell one passenger a ticket, or the time taken for a passenger to claim luggage is variable; the program, each time it simulates such an event, samples from the 'serving time' distribution provided as input. As a consequence, even if all design variables are held
constant, a repeat run of the program will result in the output of different performance measures; thus, letting the program operate iteratively will eventually turn up that particular set of extreme conditions which the building will ultimately have to cope with.

Modification. Based on the evaluation the designer can purposefully explore changes in the design variables and in the context variables. Changes in the design variables would be carried out with the intention of getting the levels of provision into "balance"; i.e., increasing the provision where queuing is excessive, reducing the provision where the server idle time is excessive. Balancing the system by iterative modification is a delicate activity as a change in the level of provision within any single facility will affect the loadings experienced by all of the facilities further on in the system.

Changes in the context variables would be made to test the robustness of the design hypothesis under changing operating conditions—the incidence of fog, the introduction of Jumbo Jets, the need for security checking, etc..

Other Applications. The computer program AIR-Q is a sophisticated classic
example of the use of simulation to model a dynamic process. The scope for the use of simulation in building design is enormous. Increasingly, it is being used to model the movement of people in transport termini—tube stations, railway stations, ferry terminals—and in other building types—museums, stadia, cafeteria, etc. Within any of these (and other) building types, simulation can focus on a particular feature of the process sub-system, for example the behaviour of lifts, escalators, pater noster, etc.

The application of computer simulation models, however, extends well beyond the field of building design. Programs embodying the same principles of logic as AIR-Q are used by designers of traffic control systems, factory assembly lines, steel production plant, etc. Hopefully, as the models become more flexible and sophisticated and as access to computers becomes easier and less expensive, the danger of technological advance outstripping our understanding of the systems we create will recede.

2.2 The Energy Sub-System

The 'energy crisis' has focussed attention on the systemic nature of the earth's resources. Increasingly, we are becoming aware of the need for husbandry of exhaustable natural resources, including fossil fuels. In the Western World, a high proportion of our energy consumption is devoted to the heating of buildings—a consumption which is now recognized to be little short of profligate.

The problem of predicting at the design stage the actual energy consumption of a building can be divided into two distinct stages. The first is concerned with the actual energy requirements needed to satisfy the demands of the activities undertaken within the building. This is found through modifying the prevailing climatic conditions by the thermal storage and lag effects of the building. In the second stage these energy requirements are further modified by the part-load inefficiencies and running characteristics of the installed plant to give the energy actually consumed by the building. Thus, the first stage is concerned with the design of the building to reduce the energy requirements (and hence consumption), while the second stage is concerned with the design of the installed plant to best match the building's energy requirements and, at the same time, minimize the consumed energy.

The computer based thermal model ESP (Environmental Systems Performance—Clarke, 1978) addresses the first stage of the design problem and is intended to aid the designer in the prediction of how well alternative design hypotheses will behave thermally. In systems terms, the design problem is as shown in Figure 6.
**Fig. 6.** An operational model of the thermal behaviour of a building seen in system terms.

**Representation.** In the program ESP, the designer represents a design hypothesis to the computer by inputting the following design variables.

- The building geometry: the shape configuration of the proposed building is input by a system of cartesian coordinates. The general polyhedral case is implemented to allow the representation of complex architectural forms.
- The construction: for all surfaces of the proposed building the thermal properties—conductivity, density, specific heat, thickness, solar heat transmittance, etc.—are input.

The prime context variable is, of course, climate. The program ESP uses annual meteorological tapes on which are recorded the hourly variation of six climatic parameters: dry bulb temperature, direct normal solar radiation, diffuse solar radiation, relative humidity, prevailing wind speed and direction.

**Measurement.** The model operation is based on an implicit numerical technique which is unconditionally stable for all computational time increments. For any building enclosure under consideration, nodes are automatically placed at appropriate points external and internal to each surface of enclosure and throughout all multilayered constructions. For each node in turn, and in terms of all surrounding nodes which are in thermal contact (by conduction, convection and radiation), an implicit difference heat balance equation is formulated. The resulting set of algebraic equations (one for each node) express all nodal temperatures and energy injections in terms of both future time and present time values. This is achieved by equating the net heat flow to each node, at the start and finish of some finite time-increment, with twice the total change in the heat stored in the region.
represented by the node in question.

The model inherently takes account of transient conduction through all multi-layered constructions. In addition, the model takes consideration of: the internal long wave radiation exchange between enclosure surfaces, the casual gains from occupants, lights, machinery, etc., the effects of short wave radiation exchange between enclosure surfaces, the shading of external surfaces, the effects of ventilation and infiltration, and plant characteristics.

For any period of simulation of the thermal behaviour of the building the program computes and transfers into a file the relevant nodal temperatures and energy injections. These filed measurements are accessible to the designer as output.

**Evaluation.** Six evaluation options are open to the designer, as follows.

- The designer can evaluate the effects of imposing complex plant and/or temperature regimes on the system, for any chosen time period. Figure 7 shows the performance of the building in warm weather if internal air temperature is allowed to 'free-float' outside occupied periods, but is held constant at 20 degrees Centigrade between 8 a.m. and noon and between 2 p.m. and 5 p.m. In this regime, an intermittent plant operating strategy is being explored with preheat allowed between 6 a.m. and 8 a.m. The graphs plot the internal air temperature, the plant input/extract requirements and the external air temperature. The next three options are special cases of this one.
Fig. 8. Computer-drawn temperature gradients through a multi-layer wall construction.

- An assumption can be made that no plant capacity is available at any time. This allows the designer to improve adverse environmental conditions by modifying the building design—i.e., the shape and construction—before considering the operation of installed plant.
- The internal air temperature may be held constant at some preselected value by allowing unlimited heating and cooling when available.
- Air temperature, alternatively, may be held within specified upper and lower limits.
- The designer can evaluate the effects of process loads from within the building, e.g., the installation of some heat generating equipment such as a computer.
- The annual energy requirements of the building can be computed and displayed (under any of the above conditions) by simulating 2 days in every month and 'multiplying-up' to obtain an annual figure.

The output formats for evaluations are extremely flexible. The designer can, for example, have displayed—as in Figure 8—the variation in temperature gradient with a south-facing exposed wall over, say, a 20 hour period, in order to evaluate the suitability of the chosen construction.

Modification. Typically, a designer might determine the frequency of occurrence and severity of unacceptable environmental conditions by utilising the second option. An insight into appropriate construction modifications to the design would then be afforded by output such as that in Figure 8. If
these modifications alone do not alleviate the conditions, or if the modifications suggested are not economical, the third and fourth options could be used to determine the order of benefits likely to accrue from the adoption of an intermittent plant operating regime. The facility to construct graphical output interactively ensures a solid information base against which modifications to the design hypothesis can be explored and evaluated.

Other Applications. The program ESP is based on a finite difference technique of implicit enumeration. The basic logic, as it relates to thermal response, is applicable to any thermally dynamic system or artifact. Thus, the same design approach could be taken to the design of a wide range of plant items such as boilers, calorifiers, gas or steam turbines, etc.

Under development, is a complementary program which will allow design investigation of complex plant configurations. The intention is to aid the designer in the comparative evaluation between, say, a 'total-energy' building and a conventional building supplied both with fossil fuels and from the national electricity grid. The logic of the systemic appraisal will be as potentially relevant to national decisions on electricity generation, district heating schemes, solar and wind power, etc., as it is to the design issues of a single building.

3.0 Total System Design

Section 2 of this chapter dealt in outline with two specific sub-systems relevant to building design. There are, of course, other sub-systems worthy of special consideration—for example, the structural sub-system. More importantly, as suggested in the section on Design Concepts, is the complex interaction of the individual sub-systems, each with the others, within the systems model of the building as a whole.

The interaction between the two sub-systems already described is fairly obvious. At one level it will be clear that the number of people congregated within any part of the building—for example, the number of passengers queueing in the baggage reclaim area of an air-terminal complex—will significantly affect the thermal conditions within that space; conversely, the environmental conditions within the different parts of the terminal will influence where passengers choose to wait out the time until aircraft departure. Thus we see that the output from one sub-system may form the input to another sub-system, and vice-versa.

At another level, the performance of two or more sub-systems may be affected concomitantly, but diversely, by one or more of the design variables. The obvious example is the effect of the layout hypothesised by the designer on both the process and energy sub-systems: the layout which makes processing of air passengers efficient may be profligate in energy
terms, and vice-versa. Thus, (as depicted in Figure 2) the designer in coping with the total system must receive feedback of cost/performance measures if he/she is to find that particular solution which is, in some sense, 'best'.

It is, of course, impossible to model the 'total' system; such a model would be as complex and unwieldy as the real world itself. The intention in this section is to indicate how the models of individual sub-systems can be 'nested' together to model what we shall call a 'total' system. This 'total' system may itself become a sub-system within a more complex schema of design; and so on. Thus, the computer-based model of the operation of a boiler may become part of a computer based model of an energy system within a building, which may in turn become part of a computer-based model of the whole building, which, in its turn, may become part of a computer based model of the urban environment, etc. Fortunately, as the scale of modelling encompasses larger portions of the real world, the models relating to sub-sub-systems can be proportionally cruder, given that doubts can be allayed by invoking the sophisticated model of the sub-sub-system as an independent design exercise.

To exemplify the concept of nested models, this section will continue to focus on building design, as represented in Figure 9. This figure summarizes the form and content of the computer program called BILD (Building Integrated Layout Design—Gentles and Unsworth, 1978). By means of a series of 'command menus' which appear on the computer screen, the designer can describe the building SITE to the computer and proceed to build up on the site a progressively detailed building design hypothesis. At the outset the designer may hypothesize a BLOCK outline which can then be detailed in terms of ROOMS; STRUCTURE and CLADDING can then be added to the building representation.

In effect, BILD is a set of nested models allowing the designer to obtain the cost/performance characteristics of the design hypothesis at progressively more detailed levels of specification. At any particular level of specification, the program will model the operational behaviour of the building—as best it can be modelled—and output cost and performance attributes. The more detailed the level of specification of the design hypothesis, the more sophisticated the computational model and hence the more reliable the cost/performance output.

Within any level, however, are representational and operational models of separate but related sub-systems. Thus, at the BLOCK outline stage, the program predicts, as best it can from the input, the process implications, the energy implications, the structural implications, the capital cost implications, etc., and provides the designer with a profile of cost/performance. Quite clearly, the accuracy of a capital cost prediction at the BLOCK outline stage in the development of a design hypothesis will be significantly lower than will be possible after the STRUCTURE and CLADDING have
Fig. 9. Representation of the form and content of an integrated and comprehensive computer model for building design.
been specified; equally clearly, however, there is little value in proceeding to a highly detailed specification of the design hypothesis if the basic geometrical form of the building is suspect.

It would be quite wrong of course if a computer aid such as BILD dictated the sequence of design decision-making. There is no suggestion that it should, or does. If the designer wishes to proceed immediately to a high degree of specification, that is quite feasible. More typically, however, he/she will develop the design progressively from a rather symbolic model to a more literal one with occasional 'sorties' forward on one or two important exploratory fronts.

At the time of writing the BILD software is nearing completion. Currently, the various stages exist as separate programs and one of these has been applied to hospital design. This program, which is known as PHASE (Package for Hospital Appraisal, Simulation and Evaluation—Kernohan et al., 1973), will now be described.

3.1 The Form and Content of PHASE

The execution of the program is carried out in two stages. The first stage involves the inspection and upgrading of data files, the second is concerned with the appraisal routines. During the operation of the program a dialogue is maintained with the designer. This controls the sequence of operations and allows the designer to loop-back within the program to a previous operation.

For the appraisal of hospital design, a considerable amount of varied information has to be stored in a databank. For convenience of use this information is structured into four basic data files—a standard data file, solution file, project file and scheme file.

The standard data file: This contains information on environmental conditions, cost and interdepartmental traffic associations. Where relevant, they are stored for each of 40 individual hospital departments. Environmental data include air change rates, occupancy numbers, hours of occupancy, percentage wall glazing, percentage roof glazing, day and night external temperatures, solar heat gains, thermal transmittance values and desired lighting levels. Cost data include elemental capital costs, service running costs and fuel tariffs. Association data are in the form of a matrix reflecting the traffic between each pair of the 40 hospital departments. These data are taken from authoritative sources such as the Department of Health and Social Security's hospital guidance publications, the Scottish Home and Health Department's Hospital Planning Notes and IHVE Guide.
The solution file: The function of the solution file is to store the cost and performance characteristics of previous projects and of earlier schemes relating to the current project. These data are accumulated automatically and are used to provide the basis for a comparative evaluation of the characteristics of one scheme against other similar schemes.

The project file: This file contains information which is likely to remain constant throughout the design project. It includes information relating to the contours and orientation of the site, the building life and interest rates. Site information is formatted by imagining a grid placed over the site. A spot height is entered on each cell of the grid. The spot heights are fed into the project file together with the angle of orientation of the grid.

The scheme file: The scheme file may be created online or, more conventionally, offline by producing a tape and subsequently reading the tape data into a file. This file contains the three dimensional description of the geometry of the proposed scheme.

The block form is subdivided into:

- Components, which correspond to hospital departments and may number up to 40.
- Elements which are used to describe a complex component by the use of rectangular blocks and may number up to six for each component.

The size and shape of each element is described by stating the x, y, and z coordinates of a reference point together with the length, breadth and height of the element and its angle of deviation from the x-axis of the site grid. From this angle the program calculates the angle to true north by accessing the project file to obtain the orientation of the site grid. This specification is compiled for all hospital departments, and when completed, forms the scheme file for the run being undertaken. Because of variations in performance specifications, operational policies, market conditions and so on, a facility for the inspection and alteration of all data prior to the execution of a program run is provided. The designer is able to obtain a printout of the listing of any file or, in a specific case, an edited version containing those lines specified for inspection.

The input check involves the display, on the screen of the graphics terminal, of either the building plan, floor by floor (Figure 10) or of an axonometric view of the whole building. Input errors can thus be detected and altered accordingly and last minute changes in design intention can be incorporated. The method of effecting these modifications is described later.

The program output is at two levels—synoptic and detailed. The synoptic output shown in Figure 11 initially contains a check output for floor areas, wall areas and roof areas. The remaining measurements are produced in
tabular form, in which each measure can be compared to a sample of results from existing hospitals with similar characteristics. When a solution has been fully worked out, it can be entered in the table as the most recently attempted project result. If four results are already entered, the first result that had been entered is deleted as the columns are updated with the new result.

The wall/floor ratio and plot ratio are accepted standards, either desirable or mandatory. Site utilization is a measure of the area of site covered by the building and reflects relative density. Plan compactness compares the plan perimeter to the circumference of a circle of equal area. Mass compactness compares the surface area of the solution to that of a hemisphere of equal volume.

Department location is a total travel factor—a figure produced from the sum of all the products of the associations and their respective distances—which reflects the performance of the proposed layout in relation to the conditions imposed by departmental association. The lift dependency factor is produced from the number of vertical journeys used in the calculation factor. From these measures, and by relating performance to the size of the hospital, an index per bed can be produced. This allows meaningful com-
<table>
<thead>
<tr>
<th></th>
<th>MWWC1</th>
<th>MWWC2</th>
<th>MWWC3</th>
<th>MWWW4</th>
</tr>
</thead>
<tbody>
<tr>
<td>NUMBER OF BEDS</td>
<td>666</td>
<td>966</td>
<td>866</td>
<td>866</td>
</tr>
<tr>
<td>AREA-TOTAL FLOOR</td>
<td>612275</td>
<td>61269</td>
<td>613573</td>
<td>61432</td>
</tr>
<tr>
<td>AREA-EXTERNAL WALL</td>
<td>28557</td>
<td>25875</td>
<td>22273</td>
<td>20687</td>
</tr>
<tr>
<td>AREA-ROOF</td>
<td>72080</td>
<td>27127</td>
<td>28209</td>
<td>28502</td>
</tr>
<tr>
<td>WALL FLOOR RATIO</td>
<td>46</td>
<td>42</td>
<td>36</td>
<td>43</td>
</tr>
<tr>
<td>PLOT RATIO</td>
<td>39</td>
<td>39</td>
<td>39</td>
<td>36</td>
</tr>
<tr>
<td>SITE UTILISATION</td>
<td>18</td>
<td>18</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>PLAN COMPACTNESS</td>
<td>12.42</td>
<td>15.03</td>
<td>15.58</td>
<td>17.36</td>
</tr>
<tr>
<td>MASS COMPACTNESS</td>
<td>24.90</td>
<td>29.19</td>
<td>28.98</td>
<td>26.90</td>
</tr>
</tbody>
</table>

LIFT DEPENDENCY FACTOR: 3.18 DEPARTMENT LOCATION PER BED: 3628 BOILERHOUSE LOC. PER BED: 2501 INDIC. CAPITAL COST PER BED: 3973 INDIC. ENERGY COST PER BED: 166

> DO YOU WISH A PRINTOUT OF (1) ALL DETAILED OUTPUT, (2) PART OF DETAILED OUTPUT, (3) NO DETAILED OUTPUT

>?

> DO YOU WISH A PRINTOUT OF
(1) 10% UPPER AND LOWER MATRIX VALUES
(2) DEPARTMENT LOCATION MATRIX
(3) BOILERHOUSE LOCATION MATRIX
(4) ELEMENTAL CAPITAL COSTS
(5) ENERGY COSTS
(6) HEAT GAIN/LOSS DIAGNOSTICS

> Fig. 11. Synoptic output from the computer comparing the performance of the current hospital design with earlier designs.

parisons of layout to be made between hospitals of differing size.

The boilerhouse location index is produced from the sum of all the products of the heating loads and their respective distances from the boilerhouse, in a similar manner to department location.

The indicative capital and energy costs are totals produced from the relative cost tables which are presented in the detailed output.

The detailed output consists of:

- Department location.
- Matrix of divergence.
- Boilerhouse location matrix.
- Detailed capital costs.
- Detailed energy costs.
- Heat gain/loss diagnostics for any specified number of components.
Fig. 12. More detailed descriptive input of the hospital floor plan showing the doors.

*Department location:* The first section of detailed output consists of a printout of all the departmental activity relationships which have not been satisfactorily met; a list of those relationships which could possibly be sacrificed is also given in order to effect an overall improvement in activity performance. If the designer cares to identify on the computer screen the positions of the doors to each department (Figure 12) the program will simulate the movement patterns over a working day and output critical journey times.

*Boilerhouse location:* From a knowledge of the department heating loads, the maximum hourly hospital load is calculated. This occurs at a particular time, for example, during a morning in January—and for this period, the product of the loads for each department and the distance from the boilerhouse to each department are summed to produce a boiler location factor. In a similar manner to the procedure adopted for department location, a matrix of divergence is produced to illustrate which departments have been located too far from the boilerhouse in relation to the heating load required in the department.
INDICATIVE ENERGY COSTS (DETAILED)

<table>
<thead>
<tr>
<th>ELEMENT</th>
<th>QUANTITY</th>
<th>RATE</th>
<th>PRESENT WORTH</th>
<th>ANNUAL EQUIVALENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>HEATING (KWDAYS)</td>
<td>234604</td>
<td>.20</td>
<td></td>
<td>30099.6</td>
</tr>
<tr>
<td>PSAL (M²)</td>
<td>7365</td>
<td>.02</td>
<td></td>
<td>166</td>
</tr>
<tr>
<td>CORE VENTILATION (M³/HOUR)</td>
<td>672134</td>
<td>.01</td>
<td></td>
<td>405</td>
</tr>
<tr>
<td>AIR CONDITIONING (MJ/HOUR)</td>
<td>52890</td>
<td>.08</td>
<td></td>
<td>235</td>
</tr>
<tr>
<td><strong>TOTALS</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>310501</strong></td>
</tr>
</tbody>
</table>

Fig. 13. Output from the computer predicting energy costs for the hospital.

*Detailed Capital Costs:* A table is produced of the capital costs for a range of elements. The elements selected are those elements whose quantity significantly varies with changes in building form. The quantity of each element, which is measured from the design proposal being appraised, is multiplied by the appropriate cost taken from the standard data file to produce a present worth for each element. The present worth is then measured over the expected life of the building to produce an annual equivalent cost for a given interest/life factor. The costs measured include the normal building elements of walls, floors, roofs, windows, etc., and in addition certain items of engineering services, including the capital cost of boilers, ventilation and air conditioning plant.

*Detailed Energy Costs:* In a similar manner to capital costs, a table of basic energy costs is compiled. These costs are produced for heating, lighting, ventilation and air conditioning as a present worth. In addition, an annual equivalent cost is produced over the expected life of the building for a given interest/life factor (See Figure 13).

*Heat Gain/Loss Diagnostics:* For any specified number of departments, a printout can be obtained of the heating loads (losses) or overloads (gains) for each department in each month of the year, at four points during the day. The loads take into account heat loss through the building fabric and from ventilation, and the heat gain from occupants, lighting and solar radiation. The standard data file is accessed for the required environmental data for each department, which together with a measurement of all the surfaces of the proposed design, are used to automatically produce loads for each
Fig. 14. Computer drawn perspective view of the hospital from a chosen viewpoint.

department. These loads are based on particular departmental characteristics of temperature, number of air changes, hours of occupancy, times of occupancy, number of occupants, lighting levels, etc., in addition to thermal transmittance and percentage glazing values appropriate to each surface of each hospital department.

Following the detailed output, or following the synoptic output if no detailed output is required, a number of options are presented. The first option allows the user to modify the form of the scheme by allowing changes in the geometry; the opportunity therefore exists to converge iteratively on a solution which, on the basis of the output appraisal and other non-quantifiable design criteria appears to be the most advantageous. The second option simply allows the user to hold the scheme, in its current state of development until some future occasion. The third option provides the user with the opportunity to add this current scheme into the solution file so that it is reproduced in the synoptic output each time the program is run and can be constantly updated.

If it is decided to change the geometry of the scheme, the program returns the user to the floor plans and provides a menu of commands which, along with the cursor, allows easy manipulation of the geometry (Figure 12). By pointing the cursor at the command menu and at appropriate reference points, the designer can move, reshape, add to, delete from, or change the scale and planning grid of the proposal.

If a perspective view of the scheme is desired, the current geometry can be stored in a file and subsequently accessed by another program which will automatically generate perspective views from any chosen viewpoint (Figure 14).
3.2 Observations on PHASE

Although it may not be clear at first sight, the conceptual approach embodied in the program PHASE is virtually identical to that embodied in the sub-system programs AIR-Q and ESP. In systems terms the inputs consist of all the design variables which specify the design hypothesis (geometry, construction, etc.) and all the context variables which modify the operational behaviour of the model (climatic data, desired environmental conditions, activity relationships, etc.). The output variables are, of course, the predicted cost and performance attributes for the hypothesised design.

PHASE models, as best the input representation will allow, both the process and energy sub-systems.

Process Sub-Systems. The input and output to the logic which models the process sub-systems are as illustrated in Figure 12. Accessing filed data on the movement pattern of nurses, food trolleys, etc., the program sub-routine simulates, over a day in the life of the hospital, the movement which takes place. For any particular nurse-journey, the program identifies the origin and the destination of the journey, invokes a 'shortest-route' algorithm from the geometrical representation of the building, and traces the route over the journey period. It is thus possible to print out journey lengths and times and the resulting congestion in corridors, and at stairs and lifts. It will be seen that this sub-routine although simpler and somewhat different, is nonetheless, in principle, similar to that in AIR-Q.

Energy Sub-System. The program ESP provides a dynamic model of the thermal behaviour of buildings appropriate to a fairly advanced stage in the development of the design. In PHASE—which is intended to be appropriate at an earlier stage in design—the thermal behaviour is modelled by a simple 'steady-state' algorithm which is capable of running on less detailed constructional data.

Other Sub-Systems. The process sub-system and the energy sub-system are only two of the many program sub-routines within PHASE, all of which operate on the design and context variables which make up the design hypothesis. Any one of them could be developed in more detail as 'free-standing' programs in their own right—in the same manner as AIR-Q and ESP.

Conceptually, the important feature of PHASE is the manner in which the disparate sub-routines are organized to operate on a single representation of the design hypothesis. As argued in the opening section of this Chapter, a comprehensive model such as PHASE is crucial to a systemic view of design decision making.
The program will in fact produce a graphical representation of the balance between synoptic cost and performance attributes. The sequence of profiles obtained from exploration and development of four fundamentally different design strategies is illustrated in Figure 15. When these measurable attributes are considered in conjunction with the aesthetic qualities embodied in the perspective views an opportunity is afforded the designer and client body to base their subjective value judgements on a shared and explicit information set.

**PHASE: in Relation to BILD.** We have seen how PHASE represents, at one level of design detail, the integration of many disparate aspects of the design problem. The program BILD is also integrative—this time over disparate levels of design detail. By extension of the principle of integration (i.e., the ‘nesting’ of appropriate models), it will be seen how the designer and others can, progressively, build up an understanding of the natural and human-made world and the complex interactions between them. Equally, it will be seen that a progression based on such an approach depends, not solely but nonetheless certainly, on advances in the science of computing.

4.0 Conclusion

In this chapter, the role of CAD has been exemplified by reference to
architecture and building design. It is worth noting that it is some 5,000
years since architectural drawings first made their appearance as models of
future reality. Up to about 30 years ago, little or no development had taken
place in these modelling techniques. Quite suddenly, with graphical access
to powerful computing facilities, vast new modelling possibilities were
opened up. In the ten years since, the progress has been rapid, but it would
be absurd to imagine that the model developers have done any more than
scratch the surface of the modelling potential. Not only is there scope for
technological advancement but also for the adoption of these techniques
within the profession; who, by and large, have remained sceptical if not
downright resistant.

Modelling is not of course a panacea for all problems: the data on which
a simulation is based must be accurate, as must the assumptions incorpo-
rated in the model, or at least known to some specified degree of accuracy.
The need for careful evaluation of options is no less important. Indeed the
strength of the computer approach is that it provides the opportunity to
examine many more alternatives in greater detail than previously. Thus in
principle allowing more consideration of the balance between objective
measures (e.g., costs) and subjective factors (e.g., aesthetics). Another poten-
tial benefit is that the design process can be “opened up” to involve more
participation by those affected by design decisions.

Some glimpses of this potential have already appeared. In one experi-
ment, several hours of TV time in California were given over to computer
modelling of highway routes in part of the State. In the studio the operators
of the computer model superimposed alternative routes for a proposed
highway on a map drawn on the graphics screen; the computer output, for
any particular route, information on construction cost, houses lost, agricul-
tural land used, etc. Viewers at home were able to phone in to suggest
alternatives which seemed to them, systematically, to provide a better bal-
ance. At a more technologically modest level, work sponsored by the
Science Research Council and the Social Science Research Council at
Strathclyde (Aitch, 1977) has shown that, with access to an appropriate
computer based design aid, nursery school teachers can develop outline
proposals for the design of a nursery school which are at least equal in
‘design quality’ (as judged by experienced critics) to those designed profes-
sionally.

However it is appropriate to point out in conclusion that we shall ap-
proach the ‘ideal state’ of design only if we consciously design our design
methods, i.e., if we are prepared to model alternatives and exercise our value
judgements in deciding between them. The computer is as powerful a tool
in reinforcing totalitarianism as it is in emancipating the individual: a con-
scious and considered choice is required.
Acknowledgments

Advances in CAD are achieved only through the commitment and effort of integrated teams of able and far sighted people from a variety of disciplines. The examples used in this Chapter are acknowledged as due to Lamond Laing and Jim Gentles (AIR-Q), Joe Clarke (ESP), Harvey Sussock (R1 D), David Kernohan, George Rankin, Graeme Wallace and Roger Walters (PHASE), Robert Aish (PARTIAL) and all other members of ABACUS, past and present.

References