Invited paper

COMPUTER AIDED ARCHITECTURAL DESIGN.
IMPLICATIONS FOR PRACTICE + EDUCATION.

Prof. THOMAS WATT MAVER
Director, ABACUS, University of Strathclyde, Glasgow, U.K.

1. CONCEPTS UNDERLYING THE NEW GENERATION OF DESIGN AIDS

Design, the highest endeavour to which man can aspire, may be defined as the activity of making explicit proposals for a change from an 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 computer-aided architectural design (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.

The computer can be seen as providing the 'engine' to the 'tool' of design methodology. Wells' distinguishes between a tool and an engine according to the following definitions:

**Tool** - a device which allows an amplification of the power which can 'manually' be applied to the task

**Engine** - a device which provides the power to drive a tool.

A spanner, a needle and a bicycle are examples of tools; a spanner allows torque to be applied to a nut more effectively than by bare hands; a needle allows thread to be pushed through material in a way which is always impossible otherwise; a bicycle allows travel over smooth ground much more effectively than on foot. The corresponding engines are: a compressed air
spanner where the engine drives an air compressor which, in turn, drives the spanner; an electric sewing machine with its electric motor driving the needle; and a motor bike with a petrol engine driving the chain which in turn drives the rear wheel.

Computer-based models of building design represent the application of an engine: the computer - to a range of appropriate tools - the increasing repertoire of design methods.

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 Heurian terminology in which 'conjecture' and 'refutation' loom large, the most useful classification of the processes within design are those of Asimow 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 - 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 paper is devoted then to the exemplification of 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.

2. COMPUTER AIDED APPRAISAL OF 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 characterise the real building. The process of computer-aided appraisal is as represented in Figure 1.

The designer, following an analysis of the problem 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 profi-
Computer Aided Architectural Design. Implications for Practice...

Figure 1 - The concept of computer-aided appraisal of building designs.

le, 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 improvement in some aspects of cost and/or performance without significant deterioration in the others. Initially, the 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 2). 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.

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.

2.1 GOAL/BIBLE: an example of an integrated appraisal model.

GOAL (General Outline Appraisal of Layouts) 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 re-design of existing buildings as it is to the design of new buildings.

The designer can represent the geometry of his/her design hypothesis to GOAL in a variety of ways; by typing in the co-ordinates, by digitising 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 3); as soon as the scheme is input to the computer, a summary of areas can be obtained (Figure 4).

The designer then 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 speci-
Figure 3 - GOAL: floor plan being manipulated on the computer screen.

Figure 4 - GOAL: tabulation of functional areas output by the program.

Figure 5 - GOAL: opportunity provided by the program to effect design or data changes.
fies the percentage glazing required. With construction specified and summarized, the program can output environmental information regarding rates of winter heat loss or summer heat gain, together with an analysis of energy loss and gain due to insolation, conduction, ventilation, occupancy and lighting. Capital and running costs are output in both summary and detailed forms. Following each section of output, the program offers the design the opportunity to change the design hypothesis (Figure 5). By this means a very large number of design alternatives and design developments can be explicitly explored in a very short period of time.

It is not solely the functional attributes (-structural, environmental, economic-) which can be predicted by computer-based models, but also the formal character of any hypothesized design. The program GOAL can be instructed to pass to the program BIBLE (Buildings with Invisible Back Lines Eliminated) a data file of the building geometry; BIBLE, using the mathematical laws of perspective, then generates perspective views of the built form from any chosen viewpoint.

Two approaches to relating the building to its site are possible. Figure 6 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 7), in this case of a proposed industrial museum.

Figure 6 - BIBLE: a perspective view of the proposed Hilton Hotel and of the existing Edinburgh townscape adjacent to the site.
Figure 7 - BIBLE: an automatically produced photomontage which superimposes the proposed building, in this case an industrial museum, on a site photograph.

The photomontage option within the program greatly facilitates program validation; one simply photographs an existing building, inputs the geometry to the program, specifies the camera position, lens focal length and print enlargement factor. The resulting view can then be overlayed on the photograph for comparison purposes.

2.2 Use of GOAL and BIBLE

The programs GOAL and BIBLE have been used in a wide range of professional and educational contexts. The case study which follows typifies the iterative search which a student is capable of making with such a powerful tool: first an exploration of geometrical forms followed by an exploration of constructional 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; a set of target costs and a target profitability were explicit from the outset.

Figure 8 presents a summary of the four formal layouts explored by the student. 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
Figure 8 - Four alternative hotel geometries compared in terms of a range of cost and performance variables, generated using the program COAL.
performance characteristics have been compared by the student in Figure 8. At this stage in the development of the design, the student made the subjective value judgement, based on the profiles of Figure 8, that scheme 4 offered the greatest potential. The second phase of the appraisal involved comparative evaluation of constructional systems as applied to scheme 4. Figure 9 provides the student's summary of the search: firstly three wall types were tested, then two levels of glazing, both single and double-glu.

The information in the bottom right-hand corner of Figure 9 is significant; it summarises the constructional choice made by the student. Instead of accepting the set of design decisions which indicated maximum profitability, based on the client's proposed tariff structure, the student 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 10) based on the output of the BIBLE program, as by the student's rigorous approach to the appraisal of design alternatives and their impact on profitability.

2.3 Programs complimentary to GOAL and BIBLE

The concept of integrated and comprehensive appraisal of buildings at an early stage in design has been exemplified by GOAL and BIBLE. Alternative - competitors if you like - to these two programs already exist and others will surely be developed. More significant than competitive models are the complementary models; these exist at higher and lower levels in the design decision-making hierarchy. GOAL, as we have seen, includes a number of appraisal routines each one of which addresses a specific subsystem within the building - structural, environmental, etc., each of these subsystems may be the focus of a separate and specific program. The concept then, is one of 'nested' models: a general model may be thought of as comprising a 'series' of 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.

3. 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
Figure 9 - A number of alternative construction choices compared in terms of costs, predicted by the program GOAL.
Figure 10 - A number of perspective views of the final hotel design, based on output from the program BISEL

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 given earlier.

3.1 Implications for Practice

The search for good solutions: Figure 1 represented the designer's 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. 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; 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 from 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 (Figure 11). Typically, the designer would select an existing building as the vehicle for his/her 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 casual relationships which provide powerful insights into the design activity.

![Figure 11 - Results of a parametric study using the program GOAL.](image)
Compressed Architectural Design. Implications for Practice...

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 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.

3.2 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 develop a modular course structure. The course will include the following modules:

i) Exposition. The concepts underlying CAAD, survey of the state of the art, and demonstrations.

ii) Preparation. Hands-on experience of a range of programs and discussion of their form, content and interfaces.

iii) Application. Using one or more programs in a studio design project.

iv) Instruction. Acquiring programming skills and knowledge of hardware and software systems.

v) Development. Specifying implementing and maintaining hardware and software systems.

Units 1, 2, and 3 are sufficient to prepare students for CAAD use; units 4 and 5 are needed if the student wishes to go on to develop CAAD expertise. The units are described in turn in the following subsections.

i) Exposition

This unit comprises lecture, seminars and demonstrations. The lecture material will include the history of computing, hardware types and trends, software concepts and artificial intelligence, the relevance of design methodology and systems concepts, a
review of computer applications in architecture (management, drafting and design), economics, problems and prospects and future trends. Demonstrations may be in-house, in other Schools and, best of all, in local practices.

ii) Preparation
This unit gives the student 'hands-on' experience in a controlled way. It is intended to introduce the student to three aspects:

i) the man-machine interface-keyboard, screen, tablet, plotter, operating systems, i.e. what button does what

ii) software logic-program, files, algorithms, documentation, i.e. how the input gets transformed into an output in various example programs

iii) data preparation-collecting, formatting and inputting the data needed for a variety of example programs.

iii) Application
This is the central unit in the modular course structure and is intended to take its place alongside conventional design projects in the U/G studio. Students would be expected, in addition to submitting plans and elevations at the final crit, to show the sequence of their search for a solution with explicit comparative evaluation of the range of design alternatives which were appraised during the project. For projects of five or more weeks, students would typically design 'from scratch'; in shorter projects, students might be given a design (say from an earlier project or from another school) as a starting point.

iv) Instruction
This unit, offered only optionally, and perhaps only in certain Schools, includes discussion of program languages (including instruction in one), databases and operating systems and of the comparative performance of micro, mini and mainframe hardware.

v) Development
Again, this Unit would be offered only optionally and only in certain Schools where the degree of access to hardware and software and to expertise was high. This final unit, with associated project time, is intended to equip graduates to fulfill a specialist role in practice - specifying, implementing and maintaining CAAD systems.

3.3 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-formalise 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 the 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 affect 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 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/her 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/her design according to his/her own criteria as an experienced user, by using subjective 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 12).

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/she 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/she considers to be an appropriate mixture of subjective qualities and objective properties.

The major conclusions and implications which emerge from an experiment in which nursery school headteachers were given the opportunity, individually and in groups, to design an 80-
Figure 12 - PARTIAL: a nursery school layout generated, with the aid of the program by a nursery school teacher.

place nursery school, are as follows:

(a) Nursery school head teachers 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 involves, but is also evaluated more highly than the participants' individual designs.

(c) Further support for the feasibility of this type of involvement comes from the finding that not only do architect evaluate the participants' designs as highly as those of architect, but also they considered the group solutions to be an improvement over the individual solutions upon which they are based.
4. 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. 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 13);

(b) a move towards models which allow 'experiencial appraisal' of the qualities of the built environment, e.g. acoustic quality (Figure 14).

Figure 13 - Computer technology and telecommunication technolo-
gy linked to promote participation in design and planning decisions.

It is most important that the architectural profession, with its deep commitment to and systematic view of the quality of the built environment should face up to and accept the challenge of CAAD.
Figure 14 - A scenario for 'experiential appraisal' of the acoustic environment in a concert hall.

5. REFERENCES


6. ACKNOWLEDGEMENTS

I am grateful to fellow members of ABACUS for their expertise and loyalty and to the European Cultural Committee and the UK Science and Engineering Research Council for purring.