Expert Systems in the Design Process

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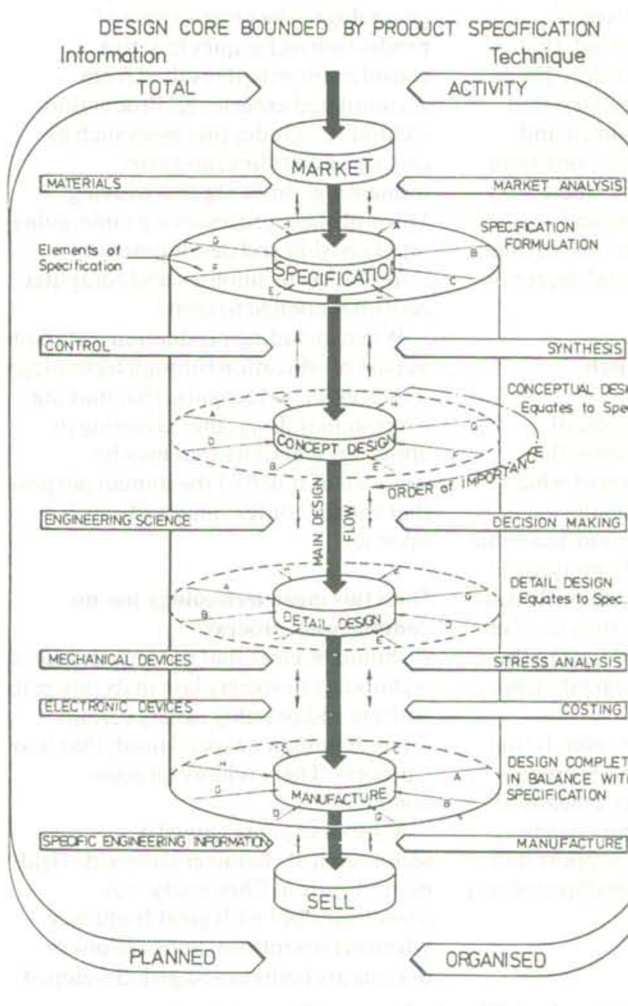
Computers have been used to aid the design process for well over twenty years. Initially there were just draughting systems, but now 3-D modellers and finite element analysis packages are commonplace. As computing power has become cheaper to buy and smaller to house so the applications for these systems have proliferated and all designers are now taking an interest. Expert systems, which try to imitate human decision-making capability, are much newer, but as with the draughting and analytical tools they will eventually find their way into the world of computer-aided design. This article discusses the possible roles of expert systems in the design process and illustrates the use of two shells — TIMM and INSIGHT — in relation to detailed design decisions. Using a shell will impose constraints on the way the problem must be formulated and the application of TIMM to the costing of turned components and INSIGHT to the selection of a manufacturing process demonstrate the kind of structures it will be necessary to use.

Expert (or knowledge based) systems have developed as a result of the fundamental research in the field of artificial intelligence conducted primarily in American Universities durng the 1960's and 1970's. This research set out to establish the methods by which humans took decisions in complex situations and to emulate this decision-making capability using computer systems. Over the last two decades many expert systems have been developed and representative examples might be those for the diagnosis of medical illnesses from patient information and engine problems from indicated faults, for the interpretation of mass spectrometer data to determine chemical structures and geological data to find mineral deposits and for the planning of construction projects and computer configurations. Most of these applications required the use of mainframe computers or specialised machines, but since 1983, and before many people expected, tools and languages suitable for building expert systems have become available on personal computers (PC's). Systems which can run on desktop PC's obviously significantly broaden the potential market, and many new applications, particularly in the business world,[1] have been identified. It was against this background that it was decided to centre the early research in the Design and Technology Department at Loughborough on the potential of the PC-based languages and tools for aiding the design decision-making process.

Human experts narrow down the area in which they seek solutions using 'rules of thumb' or 'heuristics' which are often extremely difficult to capture or define. Even with the most powerful computers now available such strategies are still essential for some types of problem to be handled, because otherwise the 'combinatorial explosion' associated with an exhaustive search of all the possible solutions is simply too time-consuming. Expert system tools (or shells) aim to help capture these 'heuristics', and languages such as Prolog to facilitate their representation in a program. Generally expert system tools fall into two categories, those which acquire decision-making skills by learning from examples and those which operate on the basis of 'production rules' of the if . . . then . . . type. The initial study was based on two such tools — TIMM, which learns from examples and was developed by the General Research Corporation in California and released in 1983 and INSIGHT, which uses production rules and was developed by Level 5 Research in Florida and released in 1984. Both run on an IBM PC which has become the effective industry standard.

In order to consider these ideas in the context of design it is necessary to have some kind of model of the process involved, and the Design Activity Model proposed by Professor Pugh seems the most appropriate.[2] This model is gaining

Fig. 1 **Design Activity Model** *(Ref. 3)*



acceptance for teaching design to undergraduate Engineering students through the work of SEED (Sharing Experiences in Engineering Design — an association of lecturers in Higher Education), and is gaining wider recognition in relation to the teaching of Design at 'A'-level. The version adopted by SEED is shown in Fig. 1.[3] The process can be seen to begin and end in the market place, and to pass through the stages — at least when viewed historically — of defining a product specification, selecting a solution concept, detail design and manufacture. Each of these stages is clearly characterised by human decision-making and in many cases these decisions are made in the face of unbounded solution spaces and limited information. Experience is also known to be a tremendous asset in managing the design process, and there must be many opportunities for using expert system tools to capture some of the designer's experience. 'Achilles' the corrosion and materials selection advisory system developed at Harewell has already tackled one application area, and systems for the selection of welding processes and procedures are under development at the CEGB and The Welding Institute.[4]

In aiding the representation of human knowledge expert system tools impose constraints on the way in which that knowledge can be represented. The tools vary from those that are very restrictive, but very easy for non-programmers to use, to those which are very flexible, but require significant training or expertise to operate. TIMM and INSIGHT are in the former class and are intended to make it possible for experts in particular fields to capture their own expertise without the assistance of specialist programmers or 'knowledge engineers'. In attaining this level of user-friendliness there is a corresponding cost in what can be achieved, and in order to demonstrate their characteristics detailed discussions of the use of TIMM in relation to cost decisions in the design process and INSIGHT in relation to the selection of a manufacturing process are presented below. A language like Prolog offers complete freedom of approach, but little assistance — it is as ever a question of selecting the right tool for a specific task.

Cost Decisions in the Design Process

Decisions concerned with cost, or with cost implications are made at all stages of the design process with very different levels of information. Fig. 1 shows costing occurring towards the end of the design process and during the completion of the detail design. Expert systems would not be an appropriate approach to establishing the likely cost of a completed design because at this stage all the information is available and the problem is susceptible to conventional programming. Software has already been developed by a commercial company[5] and The Welding Institute[6] to facilitate cost estimation for welded fabrications. However it is well-known that once the design is complete the irreducible cost of the product has been determined,[7] and therefore it has been reasonably argued that if designers had cost information as they made decisions they would be both more likely to achieve target costs[8] and optimal value. The approach adopted to the prediction of costs earlier in the design process in the late seventies and early eighties at the Loughborough University Engineering Design Centre at Birmingham University was the development of regression equations. This involved the identification of key predictive variables associated with manufacturing processes — Mahmoud for turned[9] and Shadravan for fabricated[10] components at Loughborough and Coates for mould tools[11] at Birmingham — the representation of these variables on numeric scales and the determination of their relationship to the manufacturing costs through the statistical analysis of historical data. A TIMM style expert system shell can improve on this approach for a number of reasons:

(1) The best match approach adopted by TIMM between the examples it learns from and the case it is dealing with means that advice will be given even if the values of some of the variables are unknown — the 'reliability' indication will however decline. It is not necessary for the designer to provide information on every variable.

(2) TIMM can handle both numeric and non-numeric variables simultaneously and treats them similarly. This means that there is no requirement to represent variables such as 'material type' on a numeric scale e.g. 1-10, which is a tiresome chore and looks 'artificially scientific'.

(3) Each new case can be added to the system's knowledge base so that it is being continually updated and evolving in line with any technological or other changes. The system's judgements are not solely based on historical data.

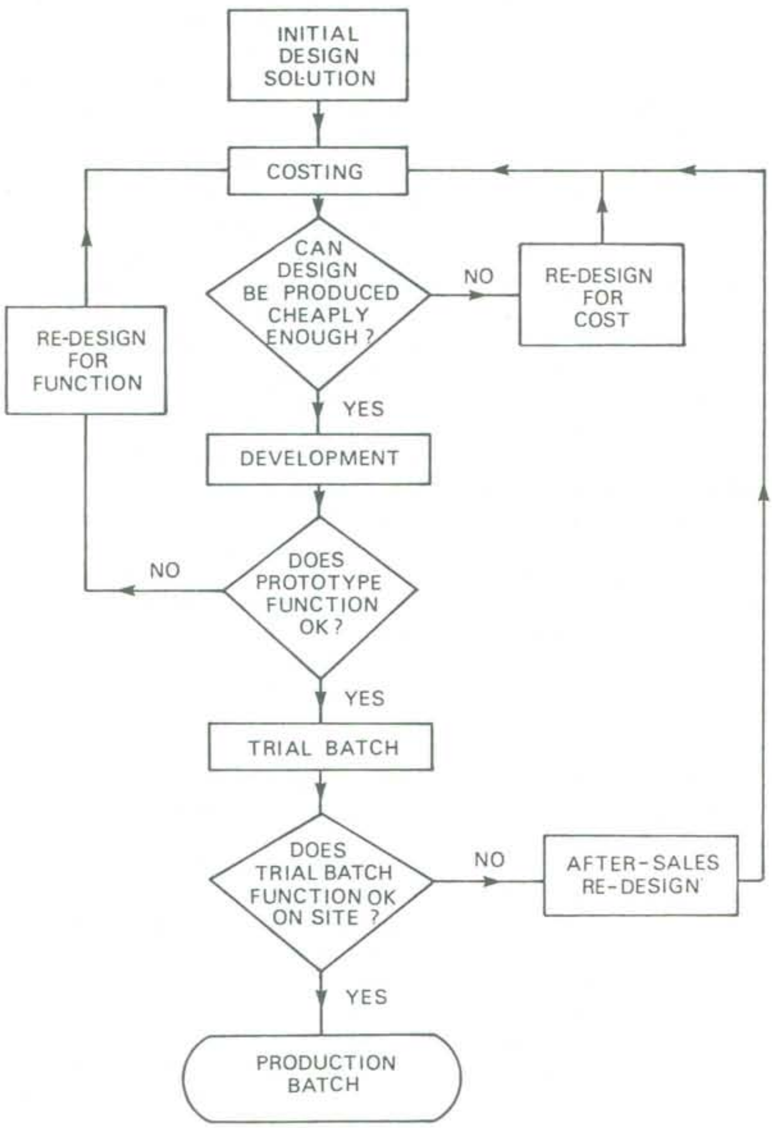
The constraints which TIMM imposes on the format for such a system are detailed below in the description of an expert system structure based on the Ph.D thesis concerning the prediction of costs for turned components prepared by Mahmoud.

The earlier in the design process that attempts are made to evaluate the cost implications of decisions the more hazy and ill-defined the problem becomes and there should therefore be considerable scope for the development of expert systems. It has been shown to be possible to consider the opportunities for 'costing concepts' before any detail design has been executed, and quite an advanced system for attempting this task has been developed in Germany. The approach taken was based on the determination of direct material costs and the establishment of relationships between these and total manufacturing costs in different industrial sectors.[12] A similar concept though less developed was proposed by Herbert Rondeau in the USA.[13] Where direct material costs do not dominate, these methods would result in considerable inaccuracy and uncertainty, but they provide an interesting starting point. A more sophisticated approach to the cost assessment of alternative project proposals has been incorporated in an expert system developed for the construction industry.[14] This system identifies the construction method implicit within the proposal, the likely time schedules and the costs associated with them. Costs related to time e.g. rents for equipment or space, lost production, capital charges etc. are likely to form a very major proportion of total costs for complex assemblies and must be taken into account in assessing alternative design proposals. Expert systems capable of accurately assessing the total cost implications for production, distribution and after-sales servicing of alternative design strategies would clearly be very useful in the assessment of design concepts, but their development will be long and arduous.

An Expert System Format for the Cost Evaluation of Turned Components using TIMM

When using TIMM it is necessary to define the decision it is required to take, the factors relevant to taking the decision, the nature of each factor e.g. numeric or descriptive, the values that each factor can take up or a range and to specify the ordering of the values. In order to use this system it is therefore necessary to recast the costing problem in the form of a decision. At the detail design stage this is in any case the 'natural' format of the problem as is indicated in Fig. 2.[15] The cost decision is of the 'yes-no' type or one of 'release for manufacture-redesign'. An experienced designer is not likely to cost out accurately each component, but merely to assess its features and to decide whether or not it represents the optimal solution in terms of achieving its function at an appropriate cost. The cost assessment will be in terms of the number of operations, the required tooling, the level of skill needed, redundant aspects etc. and not in terms of monetary units.

Fig. 2 **Iterative Design Procedure** *(Ref. 15)*



The equation Mahmoud developed for predicting the cost of turned components at the design stage is given below with a brief identification of each variable. The component cost, C, is based on the determination of the manufacturing floor-to-floor time and the total material cost.

$$C = \frac{R}{60} . Nd \left[\frac{L.Dm.Kc}{4.8} + \frac{St}{X.Q} \right] + Mc$$

where:—

R is the company's hourly rate (£/hr)

Nd is the component complexity factor based on the number of machining features and set-ups

Kc is a combined factor representing the required tolerance and surface finish, the material and machine types

L is the total machined length

Dm is the component mean diameter

St is the machine setting time

X is the machine tooling factor

Q is the batch size

Mc is the total material cost including wastage and scrap.

Table 1 shows these variables in TIMM format. Once TIMM knows the variables to be considered all that remains is to give the system enough examples for it to gain experience. Each example forms a node in the solution space and when asked to evaluate a new component TIMM will calculate the 'distances' from various nodes until it finds the best match. The distance away of a partial match gives the measure of reliability. Such a system is capturing the knowledge of experienced design evaluators, continually learning from all new cases and making this expertise available to all — the essence of an expert system.

Selecting a Manufacturing Method

One of the ways a designer can significantly influence the manufacturing cost, and hence the commercial viability of a product, is through the careful consideration of manufacturing requirements. The manufacturing method needs to be selected as early as possible in the design process so that any constraints on the product form can be properly taken into

Table 1: **Summary Table of the Factors for a Possible TIMM Format of an Evaluation System for Turned Components**

FACTORS	FACTOR VALUES	PHRASE TYPE	ORDER TYPE
Target cost (£)	Min. value: 1 Max. value: 50	numeric	linearly ordered
Discontinuity factor	Min. value: 5 Max. value: 19	numeric	linearly ordered
Machining factor	Min. value: 1 Max. value: 15	numeric	linearly ordered
Material type	Mild steel/Cast iron Duralumium/Bronze Alum. die cast/Cast brass	descriptive	linearly ordered
Machine type	Centre lathe/Capstan lathe/Combination turret/Automatic Junior/ N.C. lathe	descriptive	linearly ordered
Total machined length (mm)	Min. value: 10 Max. value: 1000	numeric	linearly ordered
Component mean diameter (mm)	Min. value: 5 Max. value: 200	numeric	linearly ordered
Machine setting time (hrs)	Min. value: 1 Max. value: 5	numeric	linearly ordered
Machine tooling factor	Min. value: 5 Max. value: 12	numeric	linearly ordered
Batch size	Min. value: 1 Max. value: 1000	numeric	linearly ordered
Scrap percentage	Min. value: 5 Max. value: 90	numeric	linearly ordered
Material cost (p/kg)	Min. value: 50 Max. value: 500	numeric	linearly ordered

account and any advantages can be fully exploited. Many factors help to determine the appropriate manufacturing method, some economic and some technical, and three of the major ones are noted below.

Quantity Required: Some manufacturing processes, such as pressure die-casting and powder metallurgy, require expensive tooling and can only be economically employed when large quantities are involved. Particular companies may have limited available tooling and in order to employ particular processes new investment may be necessary — there will be a breakeven volume below which this cannot be justified. Machining from stock materials is labour intensive, but cost-effective for small batch sizes.

Material Selected: The material selected for a component must meet the service requirements in terms of mechanical properties such as tensile strength, hardness and toughness and physical properties such as thermal conductivity and corrosion resistance. Materials are usually suitable for either casting or working and this type of obvious limitation must be taken into account. Equally, such necessary requirements as a low melting point for die-casting and considerable ductility for presswork must be recognised.

Required Accuracy: The tolerance allowed on a dimension or the specified surface roughness will help to define the most appropriate manufacturing route. Information on the accuracy of various casting methods and the roughness associated with particular manufacturing methods can be found in reference 7. For example, the best tolerance which can be achieved on a length for a sandcasting is approximately ± 0.5mm per metre (PD6470:1981) and the finest surface roughness normally obtainable by milling is 0.8μm (BS1134:1972).

An Expert System Format for the Selection of a Manufacturing Process using INSIGHT

INSIGHT requires the definition of the goals of the system which represent the major conclusions that the knowledge base can reach, and the provision of production rules by which they can be proven. The primary goals for this system might be presented as

1. The most appropriate method is SANDCASTING
2. The most appropriate method is PERMANENT MOULD CASTING
3. The most appropriate method is DIE CASTING
4. The most appropriate method is INVESTMENT CASTING
5. The most appropriate method is FORGING
6. The most appropriate method is FABRICATING
7. The most appropriate method is MACHINING FROM STOCK
8. The most appropriate method is POWDER METALLURGY

9. The most appropriate method is INJECTION MOULDING
10. The most appropriate method is VACUUM FORMING
11. . . . .

For many components some surfaces will require specific finishes i.e. machined surfaces on castings etc. This secondary processing could be represented by sub-goals e.g.

1. The most appropriate method is SANDCASTING
   - 1.1 Finishing should be by END MILLING
   - 1.2 Finishing should be by SURFACE GRINDING
   - 1.3 Finishing should be by SHAPING
   - 1.4 Finishing should be by REAMING
   - 1.5 . . . .

In order to select from these goals INSIGHT uses production rules in the following form:—

RULE For choosing SANDCASTING
If the quantity required IS large
AND the product shape IS complex
AND the material is cast iron
AND the required accuracy is <0.5mm/m
THEN the most appropriate method is SANDCASTING
CONFIDENCE 80%

The confidence statement represents the level of uncertainty that the system builder has in this particular rule. In order to select one of the sub-goals rules of the following form would be required:—

RULE For choosing REAMING
IF the required surface roughness is $\leqslant 0.8\mu$m
AND the surface to be finished IS cylindrical
THEN finishing should be by REAMING
AND SANDCASTING
CONFIDENCE 60%

The INSIGHT package is capable of holding many hundreds of such rules on an IBM PC and hence making available a wealth of expertise to a designer. In seeking to prove the validity of one of the goals it will use the rules to gather appropriate information from the enquirer in order to reach a conclusion. During the process it will calculate an accumulated 'confidence' and if this falls below a 'threshold' level, or the system runs out of rules to try INSIGHT will indicate that it is unable to reach a conclusion.

Other Possible Applications within the Design Process

Aircraft design is a complex process where new designs take a long time to evolve, typically twelve years between designs for aircraft used by airlines.[16] Consequently, there are many personnel changes between designs and a very real need exists to find a way of preserving and transferring design expertise. This has provided the basis for an ESPRIT project to develop an expert system called 'Adroit' being carried out between Cranfield Institute of Technology and the University of Munich. The system helps to break down the overall design into simpler objectives such as the design of the wing or the fuselage and then keeps a careful check on the compatibility of design decisions. With such complex assemblies and long design times such systems are potentially of immense value, but their development would be more difficult to justify for simpler products with shorter life cycles. Car and motorcycle manufacturers are, no doubt, looking at the possibilities already, if not in this country then abroad.

'Achilles' — the expert system helping to provide a corrosion and materials selection advisory system at Harewell has already been mentioned, and is really a 'smart front-end' for a database controlling the searching process. It would be expected that systems aimed at helping with the selection of mechanical or electrical components might also be developed. The problem of mechanism information retrieval has already been looked at in some depth — a study which highlighted the difficulties of representing mechanisms without sketches[17] — but perhaps a major effort incorporating computer graphics might bring this problem within reach as well.

Expert system tools such as TIMM are fundamentally aiming to emulate the human capability for pattern recognition knowing key information, and in the commercial world are finding applications in the identification of good and bad risks for insurance and investment proposals. A similar problem arises when new product ideas are screened, and it is perhaps not too far-fetched to imagine a system built using TIMM and helping to fulfill this role. One formal method currently used for new product screening is based on 'weighted' scores associated with the significant factors identified as determining product success:—[18]

e.g. COMPANY IMAGE

Weakens company image	−2	Weighting factor 2
Inconsistent with image	−1	
Makes no difference to image	0	
Strengthens image	+1	
Strengthens image very considerably	+2	

TECHNOLOGY

Very different technology unfamiliar to the company required	−2	Weighting factor 5
Fairly different technology unfamiliar to the company required	−1	
Different technology but familiar to company	0	
Similar technology	+1	
Similar technology some capacity available	+2	

The weighted scores are recorded and added in order to compare market ideas or products. It is not difficult to imagine an expert system shell like TIMM performing this role.

Concluding Remarks

Expert systems are a new technology and there has been a tendency to oversell their capabilities. This is why quite detailed descriptions of possible system formats have been given in order to try to indicate clearly the possibilities. It is hopefully apparent that with careful selection of the problem to be tackled and thoughtful representation of the associated knowledge there is considerable potential for the use of expert systems by designers. At the present rate of progress it is quite conceivable that within a few years CAD systems will be extended to incorporate advisory expert systems tackling problems rather less well defined than the stress analysis programs etc currently deal with. Within ten years expert systems will probably be just another design tool accepted in the same way as draughting packages and finite-element analysis are today.

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