Mechanical engineering design decisions: instances of practice compared with theory

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Decisions made in an engineering company were recorded and analysed to show how elementary techniques of decision-making can aid the planning and control of decisions in engineering design.

1 INTRODUCTION

Engineering design proceeds in British firms largely independently of theories about how it can be planned and controlled. Or so it appears from statements from industry and participation in Institution meetings. Expertise in the product, process, system or structure being designed is recognised as necessary. Expertise in planning and controlling such work is assumed to be gained from experience. Few engineers and engineering managers recognise that there may be common principles and lessons relevant to any design work (**1**).

There is no lack of theories and techniques on how engineering design should be planned and controlled, much of them being in terms of mechanical engineering (**2**). In this Institution and elsewhere several papers have been presented that show that design is essentially a sequence of decisions and that systematic planning of these decisions could provide a basis for controlling the work. What is not so certain is whether these recommendations are used and are successful (**3**).

Also of potential value in engineering are theories about decision-making developed by psychologists and by operational researchers. These theories have been evolved about decisions in general, but with the emphasis on management rather than engineering decisions (**4**).

To help close these gaps between theory and practice the author recorded the decisions made in a firm in the course of the design of three projects and then studied whether theories on decision-making could explain the success or otherwise of the results (**5**). Decisions were recorded over a period of nine months. This was done as an extension to the author's (RT) role and responsibilities as chief engineer in charge of design and development in the firm. Analysis of the decisions followed, as their consequences became apparent. This was an empirical study, not an experiment in altering the way in which decisions were made. The design work proceeded in the firm with only the chief executive being aware that decisions were being recorded for subsequent analysis. The results presented here are therefore based upon practice as it occurred in a firm.

The three projects observed were different in the extent that they included innovations and that they were designed to a customer's requirements. The decisions made in their design are now summarized, and then compared with theories.

2 DESIGN DECISIONS IN PRACTICE

2.1 Project A

This project consisted largely of adapting previous designs to produce plant to process synthetic fibre. It was designed to suit a customer's order. Some special design was therefore required, but quick delivery and a low price had been offered on the basis of utilizing many components in stock.

Because of this no consideration was given to reviewing or revising the existing drawings and parts lists from previous projects that could be used unaltered, because these had already been proved to work and there was limited time to deliver the plant.

Design attention was concentrated on the customer's special requirements which are listed in Table 1 together with the alternatives considered and the reasons for the final choice.

Several decisions were made because of the customer's preferences, mainly those stated in the order but also some stated afterwards and accepted at no extra charge to maintain good relationships with that customer.

Where information for a design decision was lacking, margins to capacity, etc. were added incurring some extra costs to the plant and therefore the company but avoiding delay in proceeding with manufacture for the delivery date promised.

2.2 Project B

This was a longer and more extended project as it was designed twice. The first machine designed was a prototype resulting from a policy to innovate. The second machine was designed to execute a customer's order. It

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Table 1 Analysis of decisions: case study A

	Decision	Alternatives	Constraints*	Constraint dimension†	Reason for choice	Level of decision
d_1	To supply new guards	1. Supply existing guards 2. Supply new guards	Time Customer acceptance	Control Need	Customer acceptance	Managing Director
d_2	Type of guard	1. Copy existing guards (definite customer approval) 2. Design alternatives (cheaper)	Time Customer acceptance	Control Need	Customer acceptance Acceptance	Chief Engineer
d_3	Lap regulator	1. Adapt existing scheme 2. Innovate	Time Cost	Control Control	Time Minimum risk	Designer referred to Chief Engineer
d_4	Drive unit	1. PIV (A) 2. PIV (B) 3. Eddy current 4. Mechanical 5. Hydraulic	Time	Control	Time Minimum risk Standardization	Designer
d_5	Terminal equipment Height of roll up	1. Fix height 2. Make provision for adjustment	Time Lack of information	Control Engineering	Minimum risk	Designer referred to Chief Engineer
d_6	Terminal equipment Roller gap	1. Comply with customer's wishes 2. Refuse to comply	Customer acceptance	Need	Customer	Managing Director/ Sales

* Engineering and/or process constraints were present in all decisions.
† According to the Ramstron and Rhenman criteria.

drew upon the results of the prototype, but not upon further innovation. Essentially the same team designed the prototype and the second machine, but under different managerial policies and with different results.

The decision to innovate and proceed with the prototype was a result of a policy intended to ensure the firm's future by producing machines considerably cheaper than their predecessors. Innovations were considered for all the sub-systems: frames, rollers, bearings, carriers, drives and feed roller arrangement. The main decisions made on these are listed in Table 2. The sequence of decisions and the alternatives considered are illustrated in Fig. 1. This diagram was drawn as a result of observing the decisions in practice. It is in the form of a 'decision tree' as derived by Marples in his classic studies of the design of more complex engineering projects in the nuclear and other industries (**3**). The authors found that such a tree depicted what did occur in the design of these relatively straightforward mechanical engineering projects.

In the example of the first decision listed in Table 2, the alternatives of steel fabrication and steel castings were considered as well as the traditional iron castings for manufacture of the main frames. Cast steel was rejected because of greater cost and no compensating advantage. Steel fabrication was then selected because it was estimated to be cheaper than cast iron. The frames were simple shapes, not much machining would be required if fabricated, and the sections considered were expected to be adequate for stability and against vibration. The cost comparisons took into account that the firm had recently closed its iron foundry and planned to convert it into a fabrication and machine shop.

Events in the manufacture and commissioning of the prototype affected these decisions. The cost advantage expected from fabricated frames was substantially lost by a decision by the production department to put the work out and the plan to have a fabrication shop was never carried out. The fabricated design proved to be inadequate for the loads on it, and reinforcing struts were required.

When the order came to design the production machines there was never any question that these would not be in cast iron. Not only had the cost advantage of the steel alternative been lost, but a new chief executive had by then set a policy of minimum risk, to achieve confidence in the machines, in the firm and by customers, and the design team were reluctant to be 'wrong' again.

2.3 Project C

This project was a new design to replace an existing range of machines in order to achieve much greater process speeds to match claims by competitors. The policy was to achieve this with machines that were reliable, could be adjusted to a variety of process materials and were simple to maintain.

Most of the design decisions depended upon the choice of machine speed. Market research provided data for a decision. After that the design team made the decisions, with little constraint on time or design cost except the priority of their attention had to be work for orders for other machines. As in projects A and B, most design could proceed on sub-systems for C independently, problems of matching being solved at the stages of agreeing layouts and deciding detail.

Innovations were considered for all the sub-systems. Important ones were introduced in the drives and the heavy reciprocating mechanisms needed. The alternatives considered and decisions made are listed in Table 3 and illustrated in Fig. 2. In this project novel solutions were chosen which promised advantages in reliability, convenience to the user or standardization, but otherwise risks were avoided. Time limited investigating some unfamiliar components that might have been considered. The products available limited the choice in decision d_6.

Table 2 Sequence of design decisions: case study B

	Decision	Alternatives	Ref.	Constraints	Constraint dimension	Reasons for choice and classification	Level and result of decision	
d_1	Frame construction material (prototype)	Cast iron Cast steel Steel fabrication	a_1 a_2 a_3	Technical	Engineering	Cost Desire to innovate	Chief Engineer	F
d_2	Type of steel section (prototype)	Castellated I-section I-section (solid) Channel section	a_{31} a_{32} a_{33}	Technical	Engineering	Engineering	Designer referred to Chief Engineer	F
d_3	Frame construction material (second machine)	Cast iron Cast steel Steel fabrication	a_1 a_2 a_3	Technical Company acceptance Customer acceptance Experience	Engineering Control/ need	Minimum risk Customer acceptance Company acceptance	Chief Engineer (ostensibly)	S
d_4	Construction material for main rollers (prototype)	Steel Cast iron	a_4 a_5	Cost Technical	Control Engineering	Cost Desire to innovate	Designer/ Chief Engineer	F
d_5	End fixing for main rollers	Internal flange Locking bush 1 Locking bush 2	a_{41} a_{42} a_{43}	Prior decision Technical	Engineering	Prior decision Desire to innovate Engineering	Chief Engineer/ Designer	F
d_6	Bearing selection	Type 1 Type 2 Type 3 Type 4 Type 5	a_{421} a_{422} a_{423} a_{424} a_{425}	Technical	Engineering	Cost	Designer	S
d_7	Construction material for worker rollers	Steel Cast iron	a_6 a_7	Cost Technical	Control Engineering	Cost	Chief Engineer	S
d_8	Construction material for carriers	Steel Cast iron SNG	a_{61} a_{62} a_{63}	Technical	Product	Engineering	Chief Engineer/ Designer	S
d_9	Carrier design (prototype)	Open Closed	a_{64} a_{65}		Cost	Cost	Chief Engineer/ Designer	F
d_{10}	Carrier design (second machine)	Open Closed	a_{64} a_{65}	Customer acceptance	Need	Customer acceptance	Chief Engineer	S
d_{11}	Construction material for main roller (second machine)	Steel Cast iron	a_4 a_5	Technical Feedback	Control	Minimum risk	Chief Engineer	S
d_{12}	End fixing for main roller (second machine)	Internal flange	a_{41}	Prior decision	Control	Minimum risk	Chief Engineer	S
d_{13}	Feed roller configuration	4 rollers 3 rollers	a_8 a_9	Prior decision	Control Engineering	Prior decision	Higher management	S
d_{14}	Support stand material (prototype)	Cast steel Steel fabrication	a_{911} a_{912}			Delivery Cost	Chief Engineer/ Designer	F

Table 2 *(continued)*

	Decision	Alternatives	Ref.	Constraints	Constraint dimension	Reasons for choice and classification	Level and result of decision	
d_{15}	Support stand material (second machine)	Cast steel Steel fabrication	a_{911} a_{912}	Technical (production)	Engineering	Engineering Feedback	Chief Engineer/ Designer	S
d_{16}	Bearing selection	Plain Needle	a_{922} a_{921}	Engineering	Engineering	Engineering	Designer	S
d_{17}	Loading	Washers Spring	a_{941} a_{942}	Lack of information	Engineering	Minimum risk	Chief Engineer/ Designer	S
d_{18}	Roller construction	Solid Tubular	a_{951} a_{952}	Engineering	Engineering	Engineering	Chief Engineer/ Designer	S
d_{19}	Choice of metal detector	Type A Type B	a_{10} a_{11}	Cost	Control	Cost	Chief Engineer	S
d_{20}	Feedsheet material	Leather Woven PVC	a_{12} a_{13} a_{14}	Cost	Control Engineering	Cost	Chief Engineer	S
d_{21}	Addition of fluted feedrollers			Process	Product	Improvement	Consultant/ Chief Engineer	S
d_{22}	Geometric relationship of feedrollers			Prior decision Process	Need Product	'Client' Acceptance	Consultant (by higher management)	S
d_{23}	Variable speed drive unit	Eddy current (1) Eddy current (2) Mechanical variator (1) Mechanical variator (2) Hydraulic variator d.c. motor Commutator a.c. variable speed	a_{2111} a_{2112} a_{2113} a_{2114} a_{2115} a_{2116} a_{2117} a_{2118}	 Size Size Size and cost Cost	 Engineering Engineering Eng. control Control	Cost Spares Minimum risk	Chief Engineer	S
d_{24}	Fixed speed drive	Leroy Sommer a.c. motor Other type a.c. motor		Size	Engineering	Engineering	Chief Engineer	S
d_{25}	Drive belts	V belts Flat belts		Space	Engineering	Engineering	Chief Engineer/ Designer	S

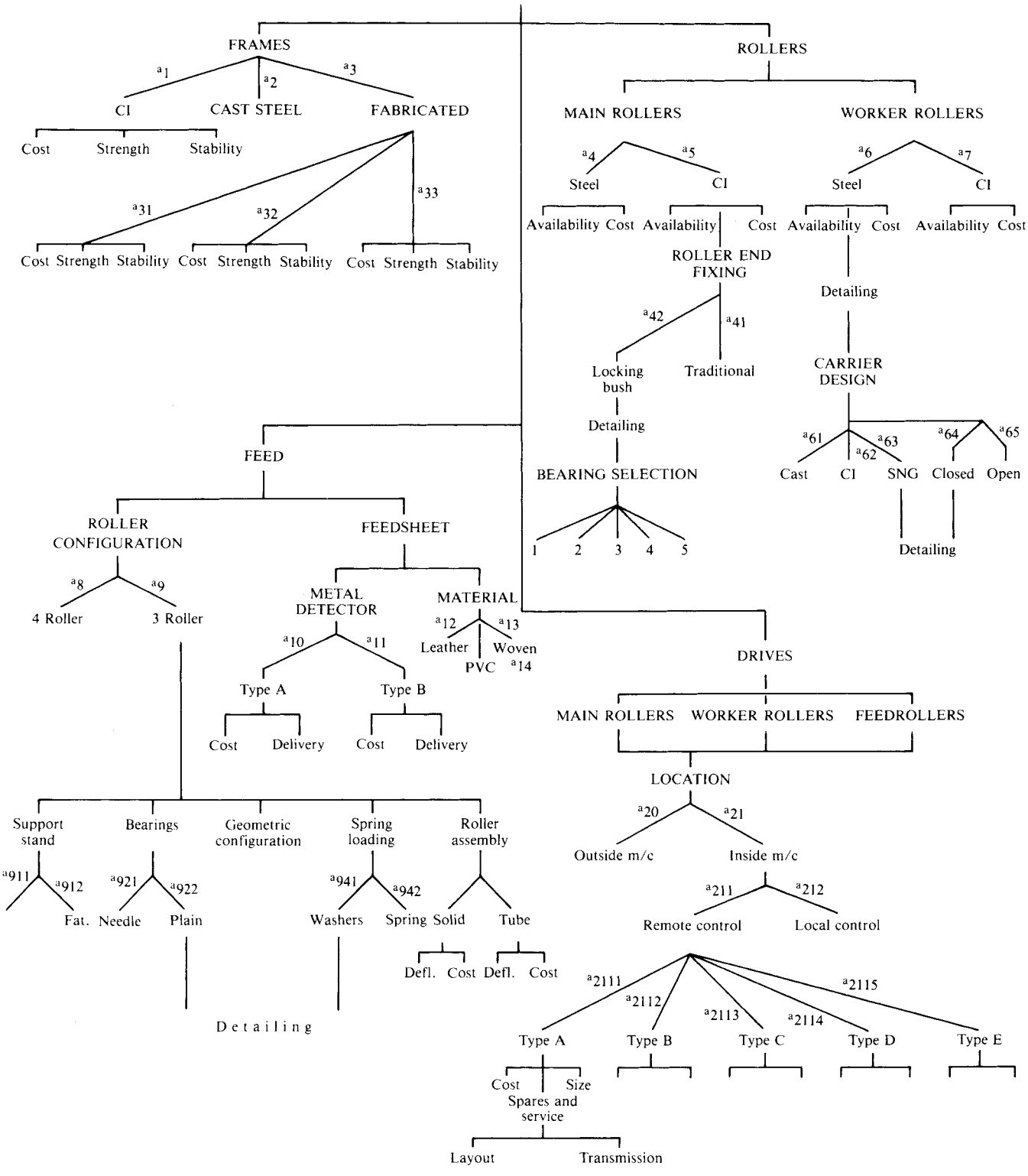

Fig. 1 Design sequence: case study B

Table 3 Sequence of design decisions: case study C

	Decision	Alternatives		Constraints	Constraint dimension	Reason for choice	Level of decision
d_1	Main drive	Contra-rotation Non-contra rotation	a_1 a_2	Experience (Engineering)	Engineering	Minimum risk Time	Chief Engineer
d_2	Reciprocating drive	Eccentric Slider Crank Link mechanism	a_3 a_4 a_5	Experience	Engineering	Minimum risk Time	Chief Engineer
d_3	Needlearm guiding	(a) Sliding block (b) Piston and cylinder (c) Linear bearings	b_1 b_2 b_3	Knowledge (based on experience) that (a) and (b) were unsatisfactory	Engineering Control (speed laid down in specification)	Improvement	Chief Engineer
d_4	Selection of linear	Type 1 Type 2 Type 3	b_{31} d_{32} b_{33}	Lack of information or response from manufacturers	Engineering	Bearing manufacture approval (minimum risk)	Chief Engineer
d_5	Needlearm material	Steel Aluminium CFRP	b_4 b_5 b_6	Weight (technical) Cost	Engineering Cost	Cost	Chief Engineer/ Managing Director
d_6	Bevel box selection	Type 1 Type 2 Type 3 Type 4	a_{11} a_{12} a_{13} a_{14}	Technical (specified backlash) Configuration Physical size	Engineering Product	Minimum risk Engineering Product	Chief Engineer
d_7	Method of balancing needle arm	Intermediate shaft Flywheels	a_7 a_7	Experience	Engineering	Engineering Feedback	Chief Engineer/ Commissioning Engineer

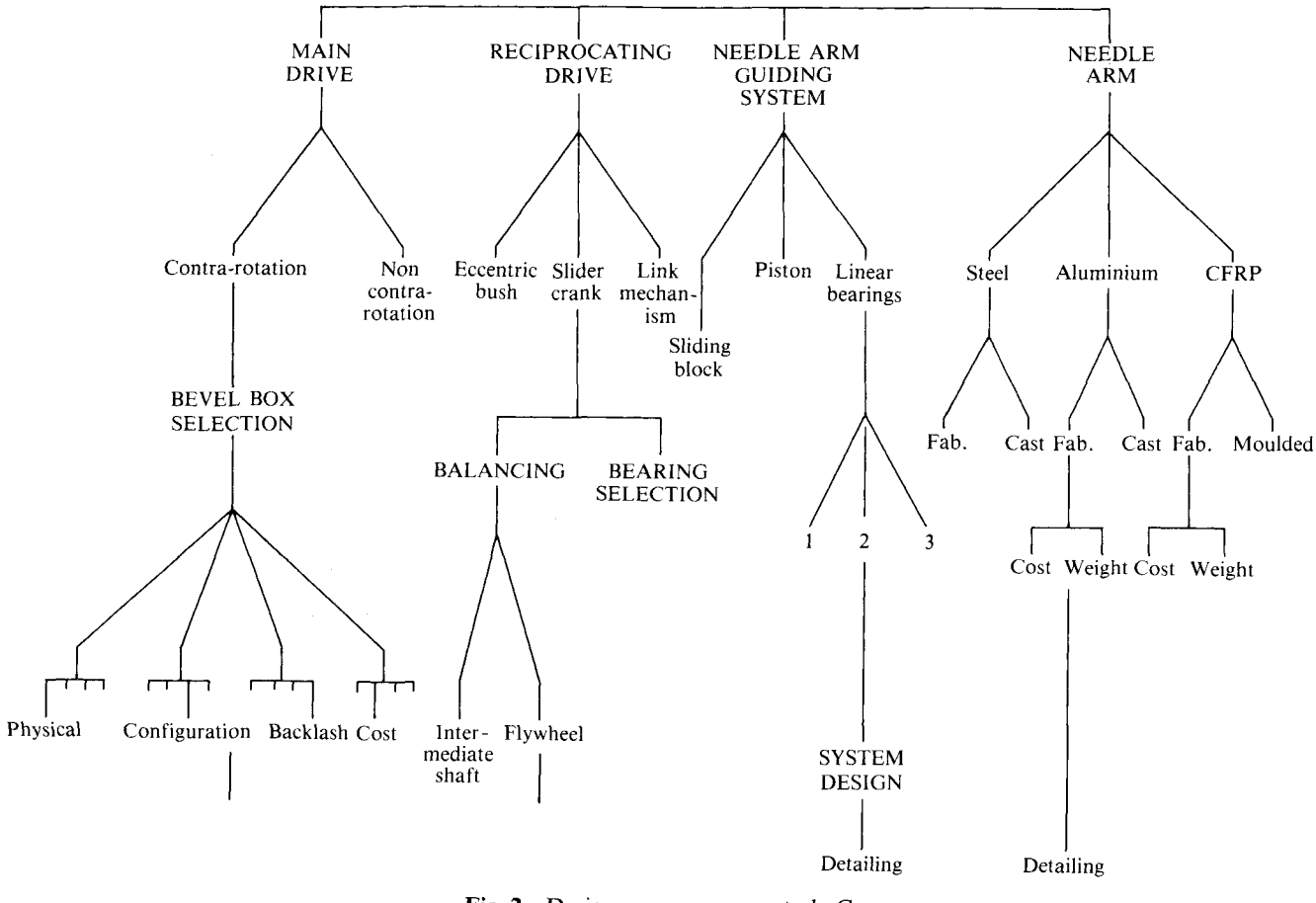

Fig. 2 Design sequence: case study C

3 THE NATURE OF THE DECISIONS MADE

In the design of Project A the majority of decisions utilized known solutions because of the almost certainty that they would be successful and time was short. Innovation relative to the design team's experience was required when such solutions were not known. Faced with unprogrammed decisions the designers opted for choices that made use of something familiar and otherwise left the maximum flexibility for solving consequential problems—exactly as had been observed by Marples.

Design of Project B was different in that tried and tested solutions were rejected up to completion of the prototype. Many of these decisions were made in a process of defining needs, listing possible alternatives, evaluation of each and ranking them for a choice. The process observed resembled the method advocated by teachers such as Asimow (**2**). The criteria for each decision were chiefly cost to customers and ease of manufacture, i.e. cost to the firm. Both depended upon predicting the outcome of unfamiliar alternatives.

In the design of the second machine the concept of relative cheapness gave way to minimizing risk to the firm. Decisions made for the prototype were thus changed to make the maximum use of known solutions. For the prototype the managerial policy was innovation and that the firm had 'nothing to spoil' in discarding its existing designs. Though the resulting innovations were successful, the change in policy led to few of the prototype features being retained.

Innovation was the policy throughout Project C, in order to match competitors. Known and novel choices were compared. Choices very uncertain in their outcome were rejected, but promising risks were taken with the back up of a rig to test them.

In all the projects there was a sequence of decisions proceeding from the general to the detailed as observed by Marples. The outcome of a decision was the start of the next. The decisions become more numerous and more detailed. The attention to each varies with its uncertainty and consequent risk, but four steps in the decision sequence can be identified:

1. Each problem was defined in engineering terms and criteria for its solution laid down. These criteria can emanate from the designers or from higher authority and may be technical or commercial.
2. A number of possible solutions were formulated. These may be simply a list of alternative materials or proprietary items or design schemes. For all practical purposes the list is considered exhaustive.

   There was evidence that in searching for alternative solutions to a problem, only relatively few are considered even if a larger number exist. Some preselection takes place on a fairly complex basis involving policy on standardization, innovation, attitude to risk, the designer's experience and feedback from other sources.
3. Each potential solution was studied using calculation, past designs and experience, and each proposal evaluated in terms of criteria laid down in the first stage. Normally engineering criteria rank highest in that any proposed solution has to be considered technically feasible before receiving further consideration.
4. Each surviving solution was further evaluated against other criteria such as commercial considerations, organizational influences, personal experience and attitude to risk. A final choice was then made in relation to these criteria and their ranking as perceived by the designers.

4 CONSTRAINTS ON CHOICES

During the various stages of the design process a number of factors influence decision-making. These can be broadly classified as organizational or engineering. Organizational values reflect both customer and management influence on decision-making. Customer specifications adopted by the company as a set of directives and controls, together with general policy constitute a set of organizational values. Such values, reflecting the need and control dimensions of Ramstrom and Rhenman (**6**), influence the decisions and behaviour of individuals and groups within the firm. Two of the most important were time and cost.

In the search for solutions the organization's objectives may become blurred by the aspirations and personal values of an individual designer. Personal values can be elusive since they are an intuitive part of the individual and may influence acceptance or resistance to organizational goals. Experience is an important guidance system by which a designer makes a choice.

In addition the personal values of a designer can also become bound up with the broader range of group values emanating from within and outside the design department, e.g. sales, shop floor, commissioning. Such values can influence decisions before or after the choice stage. There was strong indication of this in Project B, resulting in a reversion to traditional methods of design in the second series of machines.

Engineering values pertaining to standard engineering practice (general engineering values) or to the process (specific engineering values) take priority over others. Failure to satisfy the relevant engineering values results in rejection.

Where conflict arose the designer usually subordinated his own values to those of the company, although the obligation may influence his attitude to risk. For example, there was more willingness to innovate and take risks when some practical assessment (e.g. test rig) was possible and the management was conditioned to expect the possibility of failure. Designers tended to reflect the attitude of the management to risk, as in Project B where change in management attitude resulted in complete reversal of design policy.

5 APPLICATION OF DECISION THEORY

Theories about decision making have evolved in operational research and the behavioural sciences (**8**). Both approaches are concerned with the influence on decision making of information, experience, values and assessment of risk. Operational research is concerned with numerical methods of choosing between a number of alternatives. Behavioural theories attempt to explain decision-making in terms of the psychology of the individual or organizational theory.

Decision processes involve evaluating a number of alternatives against a set of objectives, the nature of

which may range from purely technical to cost and confidence parameters. The general operational research approach is to construct a matrix showing a pay-off resulting from each alternative judged against each objective. Such pay-offs are expressed in monetary terms or a utility measure of how close an alternative meets each objective. The choice is made by applying various criteria suggested as providing a rational basis for selection and which are well described in the literature (**6**).

In an attempt to assess the application of elementary quantitative methods of decision theory, pay-off tables were constructed and various decision criteria applied to several of the decisions observed in the study. The exercise was performed after the actual choice had been made, and not as a means of making the choice. Although not the way most designers would consciously make a choice, it presents a framework for comparing observed decisions with those predicted by decision theory.

To illustrate the method two examples are given: (*i*) the choice of a drive unit from Project A; and (*ii*) choice of frame material from Project B.

5.1 Choice of drive unit

A choice between five alternative drive units, S_1–S_5, was made on the basis of four objectives, i.e. cost, N_1, standardization with other units on plant, N_2, additional features offered as standard, N_3 and confidence based on experience, N_4.

In order to assess each alternative, S_1–S_5, against each of the above criteria it is necessary to assign a meaningful 'utility' value expressing the degree of fit.

In relation to cost, N_1, a straightforward comparison can be made on the cost of each unit.

The main problem is assigning values for the other criteria in relative monetary terms. However an estimate of additional spares required if a type of unit not already on plant were chosen could be made, N_2, whilst the additional cost of incorporating required features could be estimated for those units not having such features as standard provided values for N_3.

Putting monetary values on confidence is more difficult. One possible method is to assign subjective relative values to each S_1 reflecting the designer's degree of confidence on a scale from 1 (absolute confidence) to 0 (no confidence) e.g.

	S_1	S_2	S_3	S_4	S_5
Probability of no problem	1	0.8	1	1	0.9
Probability of some problems	0	0.2	0	0	0.1

The cheapest unit with a confidence rating of 1 is S_1 (£355). Given problems with S_2 or S_5 the cost of supplying an S_1 unit (plus freight, say £50) could be used, thus:

	S_1	S_2	S_3	S_4	S_5
N_4	£0	405 × 0.2 = £81	0	0	405 × 0.1 = £40.5

The decision matrix becomes:

	N_1	N_2	N_3	N_4	Min. value	Max. value
S_1	−355	0	−50	0	−355	0
S_2	−300	−40	−50	−81	−300	−40
S_3	−435	0	0	0	−435	0
S_4	−385	−20	0	0	−385	0
S_5	−485	−60	−25	−40.5	−485	−25

(The negative signs signify a cost)

The maximum criterion chooses the largest of the minimum values, i.e. −£300 corresponding to S_2. The maximax criterion chooses the largest of the maximum values, i.e. 0 leading to a multiple choice of S_1, S_3 or S_4. The minimax regret criterion is applied by first constructing a regret table by subtracting each entry in a column from the largest in that column.

	N_1	N_2	N_3	N_4	Max. value
S_1	55	0	50	0	55
S_2	0	40	50	81	81
S_3	135	0	0	0	135
S_4	85	20	0	0	85
S_5	185	60	25	40.5	185

The choice is made by selecting the smallest of the maximum values, i.e. 55 corresponding to S_1.

In practice equal weightings may not be assigned to each factor, N_j. Ranking these in order and arbitrarily assigning weights of 4, 3, 2 and 1, the matrix becomes:

	N_1 (2)	N_2 (4)	N_3 (3)	N_4 (1)	Weighted total cost (expected value)
S_1	−355	0	−50	0	−860
S_2	−300	−40	−50	−81	−991
S_3	−435	0	0	0	−870
S_4	−385	−20	0	0	850
S_5	−485	−60	−25	−4015	−1325

On the basis of expected value the choice would be S_4. In fact the choice was S_3 and the above weightings are therefore not a true reflection of the designer's attitude. To produce the actual result would mean increasing $N_2 > 5$ and $N_3 > 3.2$. This is moving towards saying that the final choice was made essentially on the basis of a single criterion.

5.2 Choice of frame material

Choice of materials were cast iron, S_1, and cast steel, S_2, in the form of a fabrication using castellated I-section, S_{31}, I-section, S_{32}, or channel section, S_{33}.

The basis of selection was made with reference to the following factors:

Strength, N_1, cost, N_2, confidence, N_3, company acceptance, N_4, customer acceptance, N_5 and desire to innovate, N_6.

In this case it is impractical to assign monetary values for the various $S_i N_j$ combinations but the combinations can be ranked in order of preference. The problem is simplified by consolidating S_{31}, S_{32} and S_{33} into a single criteria S_3, steel fabrication (since if S_1 or S_2 are chosen S_{31}, S_{32} and S_{33} are not applicable).

These are ranked in preference order assigning the value 3 to the most favoured and 1 to the least favoured and the various N_js weighted to discriminate between them, the matrix becomes:

	N_1 (2)	N_2 (4)	N_3 (3)	N_4 (6)	N_5 (1)	N_6 (5)	Max.	Min.	Expected value
S_1	2	2	3	1.5	2	1	3	1	37
S_2	2	1	1.5	1.5	2	2	2	1	33.5
S_3	2	3	1.5	3	2	3	3	2	55.5

The corresponding regret table is:

	N_1	N_2	N_3	N_4	N_5	N_6	Max.
S_1	0	1	0	1.5	0	2	2
S_2	0	2	1.5	1.5	0	1	2
S_3	0	0	1.5	0	0	0	1.5

Choices made by applying the various criteria as summarized in Table 4 are predominantly S_3.

A second choice has then to be made between S_{31}, S_{32}, S_{33} by a repeat of the above procedure.

	N_1	N_2	N_3	N_4	N_5	N_6	Max.	Min.	Expected value
S_{31}	2	3	2	2	2	2	3	2	13
S_{32}	2	2	2	2	2	2	2	2	12
S_{33}	2	1	2	2	2	2	2	2	11

The corresponding regret table is:

	N_1	N_2	N_3	N_4	N_5	N_6	Max.
S_{31}	0	0	0	0	0	0	0
S_{32}	0	1	0	0	0	0	1
S_{33}	0	2	0	0	0	0	2

The choices are therefore:

Maximum	S_{31} or S_{32}
Maximax	S_{31}
Minimax–regret	S_{31}
Expected value	S_{31}

Here the designer is largely indifferent but marginally in favour of S_{31} (the actual choice).

On the second machine the weighting assigned to the N_js were completely changed. Also, in the light of experience, the cost of fabricated frames ($S_3 - N_2$) had increased and the new decision matrix and regret table are shown below:

	N_1 (5)	N_2 (2)	N_3 (5)	N_4 (5)	N_5 (3)	N_6 (1)	Max.	Min.	Expected value
S_1	2	3	3	3	3	0	3	0	55
S_2	2	1.5	1.5	2	2	0	2	0	36.5
S_3	2	1.5	1.5	1	1	0	2	0	28.5

	N_1	N_2	N_3	N_4	N_5	N_6	Max.
S_1	0	0	0	0	0	0	0
S_2	0	1.5	1.5	1	1	0	1.5
S_3	0	1.5	1.5	2	2	0	2

Choices are shown in Table 4 along with further comparisons.

Table 4 Application of decision criteria to observed decisions

Example	Maximax	Maximin	Minimax regret	EUV/EOL	Actual
1	S_1, S_3, S_4	S_2	S_1	S_4	S_3
2(b)	S_1, S_3	S_3	S_3	S_3	S_3
3	S_{31}	S_{31}, S_{32}	S_{31}	S_{31}	S_{31}
	S_1	S_1, S_2, S_3	S_1	S_1	S_1
3	S_1	S_2	S_2	S_2	S_2
4	S_1, S_2, S_3	S_4	S_1, S_3	S_1, S_3, or S_4 (if n $\geqslant$ 2000)	S_3

The methods described above are applications of elementary decision theory to design decisions. No particular merit is claimed for them other than the inclusion in one evaluation of all the major factors affecting the decision. Some method of assigning utility values can usually be found in the terms of monetary value or subjective assessment. Weighting factors is more difficult. In practice it might be practical to start with a simple ranking order as weights and then evaluate the alternatives using different weights (but same rankings) to determine the sensitivities of outcome to different assumptions.

6 SUMMARY

Although the application of elementary quantitative techniques at the evaluation stages appears feasible, their value as a method of incorporating all these dimensions into a single model is unproved. Whilst useful as a means of dealing with uncertainty this has to be balanced against a number of measurement problems and increased time and cost.

The observations did not wholly support the view that design is a logical progression towards some optimum solution. In many cases external influences over which the designer has no control were present. There was evidence that due to constraints of time and cost the search for alternatives was limited and restricted to a small number. There was also a tendency for designers to employ rather simple choice criteria and some indication that making decisions within such constraints leads to choices which satisfy rather than optimize objectives. That is to say the chosen solution was one the designer felt took account of the rules and policies of the organization, attitudes of higher management, the forms of their profession and pressure of their environment.

Although several methods of systematic design were observed, these appear to have evolved as the designers' personal methodology rather than the formal application of published techniques. Amongst the methods observed were (*i*) experience, (*ii*) modification and running redesign, (*iii*) checklists, (*iv*) breaking design into smaller sub-problems. These are closely in line with those suggested by Eder (**2**).

Any comprehensive model of design decision-making has to develop from the fields of systematic design, system engineering and relevant aspects of the behavioural sciences.

The value of decision-making theory to engineering design may therefore lie in helping us to a better understanding of the design process rather than in the formulation of a model of design decision.

NOTES AND BIBLIOGRAPHY

1 This gap between practice and theory is seen in two ways:
(a) papers on engineering advances and innovations rarely report how decisions were planned and controlled;
(b) meetings on design methods are not well supported by engineers responsible for design in industry.

2 For books on how engineering design should be planned and controlled see for instance:
Asimow, M. *Introduction to design*, Wiley, 1962.
French, M. J. *Engineering design: the conceptual stage*, Heinemann, 1971.
Eder, W. E. In conference *Teaching of engineering design*, edited by P. J. Booker, Institution of Engineering Designers, 1964.
Pitts, G. *Techniques in engineering design*, Butterworth, 1973.
Siddall, J. N. *Analytical decision making in engineering design*, Prentice Hall, 1972.
Svenson, N. L. *Introduction to engineering design*, Pitman, 1976. For recent thoughts on design processes:
Jones, J. C. *Design methods: seeds of human failures*, Wiley, 1981.

3 For analyses of engineering design in practice in the UK see:
Hykin, D. H. W. and **Lamin, L. C.** Report of a field study of design in the UK engineering industry. *Proc. Instn Mech. Engrs* 1975, **189**, 203–211.
Marples, D. L. The decisions of engineering design. *The Engineering Designer*, Dec. 1960, 1–16.
and the book:
Langrish, J. *et al. Wealth from knowledge*, Macmillan, 1972.

4 See for instance these textbooks on decision theory:
Edwards, W. and **Tversky, A.** *Decision making*, Penguin, 1967.
Harrison, E. F. *The managerial decision making process*, Houghton Mifflin, 1975.
Moore, P. G. and **Thomas, H.** *The anatomy of decisions*, Penguin, 1976.
Welsch, L. A. and **Cyert, R. M.** *Management decision making*, Penguin, 1970.

5 **Tebay, R.** *Decision making in engineering design*, MPhil Thesis, University of Bradford, 1982.

6 **Ramstrom, D.** and **Rhenman, E.** *A method for describing the development of an engineering project*, Scandinavian Institute for Administrative Research, 1966.
Coyle, R. G. *Decision analysis*, Nelson, 1972.
Starr, M. K. *Product designing and decision theory*, Prentice Hall, 1963.

7 **Drucker, P.** *The practice of management*, Heinemann, 1955.
Simon, H. A. *The new science of management*, Harper, 1960.
Soelberg, P. Unprogrammed decision making. In *Studies in managerial processes and organisational behaviour*, edited by J. H. Hunter, Glenview, Scott and Foreman, 1972.