School of Industrial Design (Engineering): Research Unit
Royal College of Art
Kensington Gore
London SW7

L. Bruce Archer D(RCA) ~~AMIED~~ ASIA

11.2

The structure of ~~the~~ design processes

Acknowledgements

The author is indebted to a number of people and to certain institutions for assistance and advice in the conduct of the case studies upon which this thesis is based, as well as in the preparation of the work itself. A particular debt is owed to the following colleagues, staff and students, all of whom were actively involved in this work for a minimum of one, and up to seven, years:

At the Hochschule für Gestaltung, Ulm, West Germany -

Horst Rittel, Norbert Linke, Karl-Achim Czemper, Gerd Beigel, Reinhart Butter, Gerda Müller-Krauspe, Jan Schleifer, Peter Schoeller and Richard Bairstow.

At the Royal College of Art, London -

Kenneth Agnew, Gillian Patterson, Doreen Norton, Pauline Benington, Reginald Talbot, Eleanor Piclot, Timothy Coward, Anthony Smallhorn, Joseph Koncelik, Peter Slann, Patrick Purcell, Stephen Bartlett, Dario de Diana, Peter Caldwell, James Goodchild, Jane Coward, Kenneth Claxton, Joseph Armstrong, Alan Brunsdon, Michel La Rue, Richard Langdon and John Oates.

There are others whose example, assistance or advice was no less valuable but, at the time of writing, had been less prolonged.

There are four institutions without whose support the work could not have been carried out at all. Chronologically, these were, firstly, DESIGN magazine, under the editorship first of Michael Farr (who later gave the author many opportunities to put his theories to the test within the framework of the Michael Farr design management organisation) and then of John Blake, both of whom commissioned a large number of special studies; secondly, the Hochschule für Gestaltung, Ulm, who, at the instigation of Tomas Maldonado, then Rektor, provided the author with a year's guest professorship in design methodology at Ulm; thirdly, the Royal College of Art, who, on the advice of Misha Black, professor of industrial design (engineering), set up the Research Unit which has housed these studies since 1961; and fourthly, the Institute of International Education, New York, which in 1964 provided a generous grant under the Kaufmann International Design Awards programme to enable this thesis to be written.

Contents

Foreword

This thesis attempts to set up a framework within which the set of skills, sensibilities and intellectual disciplines that, taken together, constitute the art of designing might be logically related so as to form the basis of a science of design. No attempt is made here to distinguish between architectural, engineering and industrial design. Indeed, it is an essential element in the philosophy underlying this thesis that the logical nature of the act of designing is largely independent of the character of the thing designed. By the same token, no attempt is made here to define 'good design'. The argument presented is concerned with the theory of navigating towards a chosen destination rather than with the identity or merit of the destination itself.

A logical model of the design process is developed, and a terminology and notation is adopted, which is intended to be compatible with the neighbouring disciplines of management science and operational research. Many of the concepts and techniques presented are, indeed, derived from these disciplines. A primary purpose of this work is to provide a conceptual framework and an operational notation within which designers might work and upon which case study analyses might be based.

The range of techniques and disciplines which might be employed at various stages in the conduct of a design project are referred to only in general terms. Different design problems, and different classes of design activity, will call for different techniques and different emphases at various stages. There is no suggestion here that all design should be conducted according to a given formula - only that the logic of any design problem may be better perceived against the background of a common framework.

In certain instances, the general form of the laws which are thought to connect certain phenomena common to most design problems is indicated. It is hoped that the logical model, terminology and notation presented will facilitate the accumulation of the case study data, and the derivation of the more precise general laws, upon which an emergent science of design must be based.

List of letters used as symbols

A
a - a state of P
B
b - a state of P
C - a context variable
c - a state of P
D - a decision variable
d - a state of P
E - the property 'expediency'
e - a state of P
F - the marginal cost % of financing a proposal
f - some function of
G -
g - a limiting state of D
H
h - a limiting state of D
I
i - a chosen state of D
J
j - an alternative chosen state of D
K
k - a state of C
L - an exemplar
l - a threshold state of P
M - an index of merit
m - a threshold state of P

N
n - an identifying letter or number
O - a goal or objective
o
P - a property
p - a degree of fulfilment of O
Q - an incidental output
q - a degree of fulfilment of O
R - the expected return % on capital to be employed (if successful)
r - an importance rating
S - the anticipated loss % on capital employed (if unsuccessful)
s - a state of Q
T
t - a value for M
U
u - the ideal state of P
V
v - the worst state of P
W - an exemplar
w - a resultant state of P
X - a proposed design
x - a resultant state of P
Y - an exemplar
y - a degree of fulfilment of O
Z - an exemplar
z - a degree of fulfilment of O

θ - an index of probability

1 Definition of design

1.1 The Shorter Oxford English Dictionary defines 'design' as follows:

Design, sb.
I.1 A plan or scheme conceived in the mind of something to be done; the preliminary conception of an idea that is to be carried into effect by action; a project. 2. Purpose, aim, intention. 3. The thing aimed at. 4. Contrivance in accordance with a preconceived plan; adaption of means to ends; pre-arranged purpose. 5. In a bad sense: Crafty contrivance; an instance of this.
II.1 A preliminary sketch for a work of art; the plan of a building or part of it, or of a piece of decorative work, after which the structure or texture is to be completed; a delineation, pattern. 2. The combination of details which go to make up a work of art; artistic idea as executed; a piece of decorative work, an artistic device. 3. The art of picturesque delineation and construction.

Design, v.
I.1 To mark out; to indicate. 2. To designate (archaic). 3. To appoint or assign (obsolete). 4. To set apart in thought for someone. 5. To destinate for a fate or purpose. II. (allied to Design, sb.I) 1. To plan, plan out. 2. To purpose, intend. 3. To have in view. 4. intransitive and quasi-passive (usually with for): To intend to go or start. III. (allied to Design, sb.II) 1a. To sketch. b. To trace the outline of, delineate. c. To make the preliminary sketch of; to make the plans and drawing necessary for the construction of. 2. To plan and execute; to fashion with artistic skill or decorative device. 3. intransitive: a. To draw, to sketch. b. To form or fashion a work of art; less widely, to devise artistic patterns.

1.2 In popular usage the term 'to design' is employed to mean 'to make the plans and drawings necessary for the construction of' and 'to fashion with artistic skill or decorative device' indiscriminately over almost the whole field of man-made objects. The latter meaning is quite prominent, and in this usage an object is sometimes described as "having been designed", when it aspires to be aesthetically attractive; and as "having not been designed", when it is not or does not aspire to be attractive. Marginal ref. 1

1.3 In professional usage the term 'to design' is employed to mean 'to plan' or 'to make the plans and drawings necessary for the construction of' in respect of almost any man-made phenomenon, for example 'to design a building, to design an information storage and retrieval system, to design an experiment, to design (the visual side of) a television programme. Marginal ref. 2

Examples of the popular usage ('to fashion with artistic skill or decorative device') are also seen amongst professional usages, mostly in respect of art-related objects such as pottery and jewellery.

However, in professional usage, there is in the verb 'to design' an element of that which is implied by the dictionary definition I.1 of the substantive 'design'. That is to say, an element of 'to conceive in the mind a plan or scheme of something to be done'; 'to conceive an idea that is to be carried into effect by action'.- although this does not appear in the dictionary definition of the verb.

1.4 The Feilden Report on engineering design defines mechanical engineering design as: 'the use of scientific principles, technical information and imagination in the definition of a mechanical structure, machine or system to perform pre-specified functions with the maximum economy and efficiency'. Marginal ref. 3

The Feilden Report also defines the term 'mechanical engineering designer' by reference to the following: "The designer's responsibility covers the whole process from conception to the issue of detailed instructions for production and his interest continues throughout the designed life of the product."

1.5 The International Congress of Societies of Industrial Design (ICSID) has defined 'an industrial designer' as: "One who is qualified by training, technical knowledge, experience and visual sensibility to determine the materials, construction, mechanisms, shape, colour, surface finishes and decoration of objects which are reproduced in quantity by industrial processes. The industrial designer may, at different times, be concerned with all or only some of these aspects of an industrially processed object. The industrial designer may also be concerned with the problems of packaging, advertising, exhibiting and marketing when the solution of such problems requires visual appreciation in addition to technical knowledge and experience." Marginal ref. 4

1.6 In this paper the term 'to design' is employed according to the broader of the professional usages, that is to say 'to design' is here defined as 'to conceive the idea for and prepare a description of a proposed system, artifact, or aggregation of artifacts'.

No distinction is drawn between architectural design, engineering design, graphic design and industrial design. This paper embodies the premise that the structure of the design act is logically identical in all these fields.

1.7 Within the terms of this definition, it is implicit that the act of describing an existing artifact or system is not a design act. The thing designed may, or may not, follow well-established lines, but it must have at least a modicum of originality, or of adaptation to new conditions, if the act of setting it out is to be regarded as design rather than plagiarism. Hence the element of innovation is always present in design.

2 The nature of the act of designing

2.1 Man sets different values on different conditions. Those values may vary from person to person and from time to time. When a man discerns that there is a discrepancy between a condition as it is, and the condition as he would like it to be, he experiences discontent. Should the feeling of discontent be sufficiently strong, the man takes action calculated to change the condition so that it more nearly approximates to the condition he desires. The condition giving rise to desire is here described as a property (of the environment), the attainment of a state of satisfaction in response to that property is described as the goal, and the action calculated to achieve it is described as a goal-directed action. Marginal ref. 5

2.2 When the action appropriate to the correction of a particular unsatisfactory condition is not apparent, a problem is said to exist. The problem may be concerned with the correct identification of the nature of the improvement required, or with the identification of the means for achieving it, or both.

2.3 The presence of the unsolved problem, acting as a barrier to the achievement of the goal, is itself an undesirable condition, requiring action to remove it. The problem-solving activity is thus itself a goal-directed activity. Marginal ref. 63

2.4 The activity of resolving the problem therefore precedes the activity of correcting the condition. For the purposes of this argument, the aims of a condition-correcting activity (implementation) will be referred to as goals, and the aims of a problem-solving activity (planning) will be referred to as objectives. Many of the objectives of a planning ~~problem-solving~~ activity will be simply the re-expression of the goals of the ~~condition-correcting~~ implementation activity to which the problem refers. Thus a goal in constructing a house might be to provide the property of durability. If the form of construction which will give maximum durability is not immediately apparent, then a problem exists. The relevant objective in the problem of deciding how to construct the house simply re-expresses the goal of providing the property of maximum durability in the construction. In addition, the activity of deciding has its own goals, such as to come to a conclusion as quickly as possible.

2.5 In paragraph 1.6 the term 'design' was defined as 'to conceive the idea for and prepare a description of a proposed system, artifact or aggregation of artifacts'. The condition in which the designer would like to be is that in which he can offer an adequate description of the proposed system or artifact. The activity of getting into this condition is a goal-directed activity as described in paragraph 2.1. Where (as is usual) the nature of the design idea and its development is not immediately apparent, then a problem exists as described in paragraph 2.2.

The activity of designing is thus a goal-directed activity and normally a goal-directed problem-solving activity. The properties which are required to be exhibited by the proposed artifact are defined by the objectives of the problem. The details of the design are the designer's conclusions as to the means by which those properties may be provided. Marginal ref. 10

2.6 In a goal-directed problem-solving activity, all the properties required to be present in the end result may be thought of as having existed, in varying degrees, in the prior, unsatisfactory situation. Some of the desired properties may have been present and satisfactory already, others may have been absent (that is to say, present in zero degree) and others may have been present, but to an unsatisfactory degree. The objectives of the activity are thus ambitions, not merely to cause those properties to be present, but to cause them to be present to a satisfactory degree or to as high a degree as possible. Each objective thus nominates a property, indicates the direction in which changes would be for the good and identifies a threshold between 'good enough' and 'not good enough' (fig 2.1) Marginal ref. 111

2.7 Since the properties referred to may be of many different kinds, and since they may be subject to different scales and units of measurement, it is convenient to introduce a convention or form of notation by which they may be more uniformly expressed: Marginal ref. 6

indent

O signifies an objective or goal

P signifies a property or condition

O(y) signifies a particular degree of fulfilment of an objective

P(x) signifies a particular state of a property or condition

2.7 (contd)

P(u) signifies the ideal state of P in respect of a given objective

P(l) signifies a minimum acceptable state of P

P(m) signifies a maximum acceptable state of P

P(v) signifies a state of P which represents total lack of fulfilment of an objective

It is clear from the definition elaborated upon in paragraph 2.6 that the degree (y) of fulfilment of an objective O is a dependent variable, controlled by the state (x) of the property P exhibited in the solution, that is:

O(y) = fP(x) (where f signifies "some function of") Marginal ref. 62

2.8 P(x) is expressed according to whatever scale is most appropriate to the property concerned (that is to say, dimensions are expressed in inches or centimetres, weight expressed in pounds or kilograms, time expressed in seconds, minutes and hours, etc.) According to the conventions adopted here, O(y) is always expressed on the scale:

O(y) = 0 (zero) when there is total lack of fulfilment of the objective

O(y) = .5 when the related property is at the threshold between fulfilling and not fulfilling the objective

O(y) = 1 (unity) when there is total fulfilment of the objective

Moreover, according to this convention, the key states of a property P defined in paragraph 2.7 are always related to the key values of degree of fulfilment of its related objective O in the following way (fig 2.2):

when P(x) = P(u) then O(y) = 1
when P(x) = P(m) }
or P(x) = P(l) } then O(y) = .5
when P(x) = P(v) then O(y) = 0 Marginal ref. 64

Paragraphs 2.9 to 2.19 below examine this relationship more closely. Paragraph 2.20 takes up the thread of the main argument.

2.9 Where the states of a property P can vary along some continuous scale, such as a scale of centimetres or kilograms, then the relationship between the degree (y) of fulfilment of objective O and the state (x) of its associated property P may be expressed in the form of a curve.

Sometimes the relationship between O(y) and P(x) is a linear one. For example, a design might be required to entail minimum wastage of the raw material (say, steel sections) from which it is made, the maximum acceptable wastage P(m) being 50% and the ideal wastage P(u) being 0% (fig 2.3). The states of property P may be expressed in terms of some convenient ratio scale for weight or volume, say pounds or cubic feet. In such cases the relationship between O(y) and P(x) may take the form:

$$O(y) = 1 + \frac{P(x)-P(u)}{2(P(u)-P(l))}$$ Marginal ref. 7

Thus, if the relevant values of P are known or can be predicted, an index of degree of fulfilment (y) of the objective O can be calculated.

2.10 In other cases, the ideal state P(u) of a property may be indeterminate or indeterminable. For example, a product may be required to be as profitable as possible, with a low limit of profitability, but no high limit (fig 2.4). In these cases the relationship between O(y) and P(x) may take the form:

$$O(y) = 1 - \frac{P(l)}{2P(x)}$$ Marginal ref. 8

2.11 In some circumstances, both the ideal state P(u) of the property (i.e. that which totally fulfils the objective) and the zero state P(v) (i.e. that which totally fails to fulfil the objective) may be indeterminate (fig 2.5). For example, a surface might be required to be smooth, with an expressible threshold between acceptable smoothness and unacceptable smoothness, but with no determinable states of P to represent total success or total failure in fulfilling the objective. In these cases, the relationship between O(y) and P(x) may take the form:

$$O(y) = \frac{1}{2} + \frac{\arctan\,(P(x)-P(l))}{180}$$ Marginal ref. 65

2.12 Again, there may be both a maximum $P(m)$ and a minimum $P(l)$ state which represent the thresholds of acceptability in a property, with the ideal state $P(u)$ lying somewhere in between. For example, the brightness of illumination of an instrument (say, a speedometer) might be required to lie between two limits of dimness and glare, with the ideal brightness at a given level in between (fig 2.6). In these cases the relationship between $O(y)$ and $P(x)$ may take the form:

$$O(y) = 1 - \frac{(P(x)-P(u))^2}{2(P(u)-P(l))^2}$$ Marginal ref. 66

or

$$O(y) = 1 - \frac{(P(x)-P(u))^2}{2(P(m)-P(u))^2}$$

2.13 Sometimes, as in the example described in paragraph 2.12 above, the values $P(x)$ of the property concerned should relate, not just to the requirements of one particular user in one set of circumstances, but to a given range of people or circumstances. The relationship between $O(y)$ and $P(x)$ might therefore be subject to statistical conditions of range and frequency distribution, so that a given state $P(x)$ of the property would be interpreted as providing a certain probability of fulfilling the objective O to the indicated degree $O(y)$ for a certain range of users (fig 2.7).

2.14 All the examples above have been related to properties whose states may vary continuously along scales based on some agreed unit or interval. Such scales are known as ratio scales or interval scales. Not all properties can be expressed on interval scales. Beauty, convenience and importance are examples. This is because there are no units of beauty, units of convenience or units of importance with which ratio scales could be constructed. However, in such cases it is usually possible to compare designs (or whatever it is that is under discussion) and to list them in descending order of merit, according to the property concerned. This rank ordered list constitutes what is known as an ordinal scale, and the act of constructing the list is called 'ranking'.

Marginal ref. 77

Marginal ref. 9

Marginal ref. 79

2.15 Sometimes, in setting up an objective for an ordinal property in a design, it is possible to select as an example another design L which can be taken as a criterion or threshold of acceptability which the new design must beat. In other words, this example represents $P(l)$ on a specially constructed ordinal scale. It might also be possible to select a number of exemplars W, Y and Z (such as competitors' designs) which could be ranked in respect of property P, to fill out an ordinal scale (fig 2.8).

The proposed new design X could be compared with the exemplars and assigned a place in the scale. The item (say, exemplar W) which is judged best in respect of property P is represented by the point P(u) on the scale and the rank of the proposed design X is represented by the point P(x). The degree of fulfilment O(y) of the objective may then be determined by the formula (see paragraph 2.9) for linear relationships between O and P, thus:

$$O(y) = 1 + \frac{P(x)-P(u)}{2(P(u)-P(1))}$$

where P(1) signifies the rank of the criterion or threshold design L
P(u) signifies the rank of the exemplar judged best in respect of P (that is, rank 1)
P(x) signifies the rank of the proposed design X

The problems of value judgement in connection with ordinal properties such as beauty and convenience are dealt with further in Section 8. ~~The techniques for ranking are referred to also in Section 10.~~

2.16 One of the difficulties sometimes encountered in ranking is that although the steps between ranks are theoretically equal, the person or group of people performing the ranking may regard them as being unequal in the real-life situation. The person or group will be referred to here as 'an arbiter'. Thus, an arbiter might decide that chair X is more comfortable than chair Y, and chair Y more comfortable than chair Z. However, he might consider that the difference in comfort between chairs X and Y is a great deal less than the difference between chairs Y and Z. He may feel that, had he been given one hundred chairs to rank, he might well have ranked chair X first, chair Y second and chair Z seventy-fifth. This concept can be more conveniently expressed as a rating scale, where the arbiter assigns chair X 100 points, chair Y 99 points and chair Z 25 points (fig ~~2.8~~ 2.9). Under suitably controlled conditions, human subjects can assign merit ratings of this kind to non-measureable properties in a reasonably consistent and repeatable way. For most arbiters, a scale of 1-100 seems to be about the most easily handled. This technique is equivalent to using human beings as indicating-instruments in those circumstances where no physical indicator is available. Within the context of a given design problem, rating scales can be a perfectly adequate substitute for ratio scales, providing that the arbiters are correctly chosen and the conditions for judgement are adequately controlled. Marginal ref. 11

2.17 There are some properties, such as the property of identity, which are not even susceptible to being ranked in order of merit or importance. For example, the use of certain listed colours for electrical wiring or pipework may be required or forbidden by statutory regulations (fig 2.10). The items in such a list ~~may be de~~scribed as being on a nominal scale, that is to say, a scale giving identities to various possible states of the property, but neither rank nor a unit of measurement, apart from the distinction "acceptable" or "not acceptable".

2.18 In a sense, according to the conventions adopted, nominal scales are merely rating scales with only two ratings - above the limit and below the limit. Similarly, ratio scales are merely rating scales where the interval between ratings is fixed at the smallest available interval of the unit of measurement. For convenience, however, the scales of all the properties of a design can be regarded as falling into three classes; ratio scales for measureable properties, ordinal scales for merit-rateable properties, and nominal scales for "acceptable/not acceptable" properties.

2.19 In all cases, having assigned limits of acceptability (u) and (l) in a property P, the degree (y) of fulfilment of the objective O emerges as a value on the scale 0-1 (fig 2.11), on calculation by one or other of the general formulae set out in paragraphs 2.9, 2.10, 2.11, 2.12 or 2.15 or by whatever other law might connect the amount of property present with degree of fulfilment of objective.

2.20 Returning to the thread of the main argument set out in paragraph ~~2.6~~ 2.7, it must be noted that few problems are concerned only with the fulfilment of a single objective. Any solution will fulfil the various objectives in varying degrees. In order to find some way of illustrating the interdependence of the degrees to which a given design will fulfil two or more co-existing objectives, some further notation must be introduced:

O_n signifies a given objective
P_n signifies a given property
} where n is an identifying number or letter

i signifies a given design

j signifies an alternative design

P(w) signifies a particular state of a property (alternative to (x))

O(z) signifies a particular degree of fulfilment of objective (alternative to (y))

Thus a given design i will exhibit state (x) of property P_1 and state (w) of property P_2, fulfilling objective O_1 to degree (y) and objective O_2 to degree (z). This can be illustrated according to the convention of co-ordinates (fig 2.12).

2.21 Similarly, the performance of two or more designs in respect of two co-existing objectives may be indicated by co-ordinates, (fig 2.13).

O(p), O(q) signify particular degrees of fulfilment of objective (alternatives to (y) or (z))

2.22 Two objectives co-existing in a problem may be referring (albeit in different ways) to the same property in the desired end result. For example, the bed of a machine tool may be required to be extremely stiff not only to maintain the alignment of slides and spindles but also to prevent the transfer of working loads to weak structural members. The property of stiffness serves two objectives. In this case the better states of the property lie in the same direction - greater stiffness. These two objectives may be described as co-operating objectives (fig 2.14). On the other hand, two co-existing objectives may refer to the same property but seek opposite ideal states. For example, a piece of equipment might need to be as light as possible in order to be portable but as heavy as possible in order to be stable in use. Such objectives may be referred to as opposing objectives. Or again, two objectives may refer to different properties in the end product (say, durability and cost) but these properties may themselves be interdependent, so that the fulfilment of the objectives, too, becomes effectively interdependent. Some objectives may, of course, be only distantly connected.

2.23 It has been seen in paragraph 2.20 that the two coincidental values of degree of fulfilment by a design of two co-existing objectives can be shown, according to the convention of co-ordinates. Where objectives are dependent the locus of the points of coincidental states of a property or properties will mark out a curve of feasible mutual states (fig 2.15).

2.24 The limiting states of the properties concerned may be similarly set out according to the conventions of co-ordinates (fig 2.16). The spaces marked off by these limits indicate the field of mutually acceptable degrees of fulfilment of the co-existing objectives. Any solution whose mutual states of the associated properties lie within this field is an acceptable solution.

2.25 Where objectives are dependent, the curve of feasible mutual states may be superimposed on the fields of limiting states (fig 2.17). In some cases a section of the curve of feasible mutual states of the properties concerned will lie within the field of mutually acceptable degrees of fulfilment of the objectives. In these cases, feasible <u>and</u> acceptable solutions are available. In other cases there might be no solution which is both feasible and acceptable. The only escape from such a situation is <u>either</u> to move one or both of the limits of acceptability <u>or</u> to introduce some inventive step to change the inter-relationship of the objectives. The former course of action constitutes a change in the performance requirements of a design, (that is, in solution by negotiation,) whilst the latter constitutes an act of invention, (that is, solution by innovation).

Marginal ref. 12

Marginal ref. 67

2.26 Where, as in most problems, there are more than two objectives, these can be taken pair by pair and expressed in the terms described above. In aggregate the interaction of fields of acceptability will constitute an n-dimensional domain of acceptability. This domain may be discontinuous, that is to say, there may be more than one acceptability-space, each bounded by limiting states for various properties, implying that there is more than one distinctive class of acceptable solutions.

2.27 Similarly, the interdependence of the curves of feasible mutual states will constitute an n-dimensional hypersurface or realm of feasibility. An important pre-requisite for an ultimate solution is that at least a portion of the realm of feasibility should intersect the domain of acceptability, producing an arena within which a solution must be found (fig 2.18).

2.28 Thus the act of designing consists in:

1 agreeing objectives
2 identifying the properties or conditions required by the objectives to be exhibited in the end result
3 determining the relationships between varying states of the properties and the varying degrees of fulfilment of their respective objectives
4 establishing the limiting and ideal states of the properties, and hence the domain of acceptability implied by the objectives
5 identifying the laws controlling the interdependence (if any) of the properties

6 ensuring that the interdependence of the properties constitutes a realm of feasibility and that this lies at least in part in the domain of acceptability

7 selecting an optimum solution within the arena thus delineated

2.29 In most design activities more than one person is involved. The people concerned may include the financial backer, the constructor, and the salesman, as well as the designer. Any one of these may be an individual or a group. Certain individuals or groups, whether or not participating in the resolution of the problem itself, are entitled to nominate objectives or limits of acceptability - for example, the user and regulatory bodies such as health and safety authorities. People, bodies of people or impersonal forces who do or who are entitled to define objectives or limits of acceptability will be referred to here as the arbiters in a problem. The set of objectives in a problem arise from the union of the sets of goals of the arbiters involved.

Marginal ref. 13

Marginal ref. 18

During the course of the problem solving activity new objectives may tend to form and reform. At any one stage the situation may indicate that the total set of objectives will prove to have been fulfilled in varying degrees, so that individual arbiters will be satisfied with the apparent outcome in varying degrees. The then prevailing discontents may give rise to new problems, or result in shifts of emphasis in the pursuit of objectives or lead to the assignment of new limits of acceptability. An examination of this aspect of the activity of designing occurs in Section 6.

Bibliography 2

Ackoff, Russell L., Scientific method: optimising applied research decisions, Wiley, 1962.

Ackoff, Russell L., (editor), Progress in operations research: Vol 1, Wiley, 1961.

Adams, E., and Messick, S., An axiomatic formulation and generalisation of successive intervals scaling, Psychometrika, 1958, 23, 355-68.

Bertalanffy, Ludwig von, General systems theory, Human Biology, 1951.

Bross, I.D.J., Design for decision, Macmillan, 1953.

Coombs, Clyde H., Psychological scaling without a unit of measurement, Psychological Review, 57, May 1950, 3, 145-58.

Dantzig, G.B., Linear programming and extensions, Princetown University Press, 1963.

Gombrich, E.H., Art and Illusion, Phaidon, 1956.

Miller, David W., and Starr, Martin K., Executive decisions and operations research, Prentice Hall, 1960.

Moroney, M.J., Facts from figures, Penguin, 1951.

Osgood, Charles E., Suci, George J., and Tannenbaum, Percy H., The measurement of meaning, University of Illinois Press, 1957.

Rittel, Horst, The universe of design, Institute of Urban and Regional Development, University of California, Berkeley.

Stevens, S.S., On the theory of scales of measurement, Science 1946, 103, 677-80.

Tavistock Institute, Interdependence and uncertainty: digest of a report from the Tavistock Institute, Tavistock Publications, 1966.

Vajda, S., An introduction to linear programming and the theory of games, Methuen, 1960.

Luce, R. Duncan and Raiffa, Howard, Games and decisions, Wiley, 1957.

Cartwright, and Zander, (Editors) Group Dynamics: research and theory, Row Peterson and Co, 1962

Starr, Martin K, Product design & decision theory, Prentice Hall, 1963

3 The systematic model

3.1 Where two phenomena are causally related, that is to say where one phenomenon is caused to occur or to change its state by the introduction or change of state of another phenomenon, these two are said to form a system. A spring balance, for example, is such a system, since adding a load to the pan causes the spring to compress an appropriate amount (fig 3.1). Marginal ref. 14

3.2 In systems terminology, the causal phenomenon is described as the input and the resulting effect is termed the output (fig 3.2).

3.3 Where information about, or energy produced by, the output of a system is used to adjust the input (for the purpose of controlling the output), this cycle is called 'feedback'. For example, in the case of the spring balance referred to previously, if the user watches the indicator and controls the amount of (say) sugar poured into the pan until the indicator reaches a desired point, this watch-and-control activity is an example of feedback. Feedback can be exercised through human perception and control, or it can be automated. Thermostats in heating systems and speed governors in engines are examples of automatic feedback (fig 3.3).

3.4 In many cases, systems are influenced by more than one input and may have more than one output. For example, an electric motor is a system in which the input of electrical energy at a certain voltage and a certain amperage will produce mechanical energy with a particular speed and power. Varying either or both the inputs will result in a variation in either or both the outputs (unless the input variations are self-compensating). A factor which could or does take up one or more of a variety of states is called a variable. This name will be applied to all the inputs and outputs in a system even where they happen to take, or have always taken, a fixed state (fig 3.4). Marginal ref. 15

3.5 Often, certain of the inputs are under the control of an operator or decision maker (for example, a designer may be able to choose the depth of a beam to be incorporated in a structure), whilst others are governed by circumstances outside the operator's control (for example, the designer will have no control over the tensile strength of the beam material). The former are described as decision variables and the latter as context variables (fig 3.5). Marginal ref. 68

C signifies a context variable

C_n signifies a particular context variable (where n is an identifying number or letter)

$C_n(k)$ signifies a particular state k of context variable C_n (where k is an identifying letter or a value according to some scale)

D signifies a decision variable

D_n signifies a particular decision variable (where n is an identifying number or letter)

$D_n(i)$ signifies a particular state i of decision variable D_n (where i is an identifying letter or a value according to some scale)

3.6 Similarly, outputs may consist of those which the decision maker wishes to control (for example, a designer may wish to ensure that a structural beam is capable of bearing a given load) and those to which he is indifferent (for example, the volume of metal in the beam). The former are here described as ~~relevant~~ desired outputs and the latter as incidental outputs (fig 3.6).

P signifies a ~~relevant~~ desired output (this is the same notation as for a property. See paragraph 3.9).

Q signifies an incidental output

Q_n signifies a particular incidental output (where n is an identifying number or letter)

$Q_n(s)$ signifies a particular state s of incidental output Q_n (where s is an identifying letter or a value according to some scale)

3.7 The incidental output of one system, however, might be the context variable of another (fig 3.7). For example, the volume of metal which was only an incidental output from the structural system referred to in paragraph 3.6 might be a context variable in another system, say, costing or building operations. Where two systems are being handled simultaneously, these two systems can be said to form a larger, or complex, system.

3.8 Where one system in a complex of systems produces outputs which affect another in the same complex, it is convenient to regard the decision variable in the first as being also a decision variable in the second (fig 3.8).

3.9 A design problem, or any other sort of problem can be expressed in systems terms. In Section 2, problem solving activities were described as being directed towards the provision of certain properties, or certain states of certain properties, in the end result. The problem is thus a system, with the decision variable(s) as input and the property(ies) as output (fig 3.9). The set of laws determining the ways in which given properties vary under the influence of different decisions constitute the external or general disciplines within which a problem must be solved. Marginal ref. 16

3.10 The way in which varying states of a property relate to varying degrees of fulfilment of a goal also constitutes a system, with the property as input and the degree of fulfilment of goal as output. The laws connecting states of properties with degrees of fulfilment of objectives constitutes the internal or specific disciplines of a problem. A complete goal-decision system is therefore a linked pair of systems, where the decision variable(s) control a property and the property controls an objective (fig 3.10). In a complex of goal-decision systems, where a decision variable may directly or indirectly control a number of properties, there may be some ambiguity as to how the goal-decision systems should be conceived. For the purposes of this argument, a goal-decision system is constructed so that it contains one and only one objective, so that the system can be identified with, and named after, the objective it contains.

3.11 In a complex of goal-decision systems, the aim is to select a set of states for the decision variables, such that the resulting set of states of the properties satisfy their respective objectives, allowing for the indirect, as well as the direct, effects of the decision variables (fig 3.11).

3.12 In real-world circumstances, the decision variables themselves may be subject to limiting values or states (fig 3.12). For example, the machinery in a factory which is to manufacture a product under design might only be capable of handling metal sheet within certain limits of thickness and width.

The state i selected for a decision variable Dn must therefore lie within the permitted range, thus:

$$D_n(i) \subset \left\{ D_n(g) \ldots D_n(h) \right\}$$

where

$D_n(g)$ signifies a limiting state g of decision variable D_n (where g is an identifying letter or number, or a value according to some scale)

$D_n(h)$ signifies another limiting state h of decision variable D_n (where h is an identifying letter or number, or a value according to some scale)

$\subset$ signifies "is contained within the set of possible states"

The set of decision variables available to the decision maker, and their limiting conditions, will be referred to as 'the design resource' (or in the case of non-design problems, the 'decision resource'). Marginal ref. 76

3.13 In some circumstances, certain states of the decision variables may be regarded as more desirable than others, not because of their good and bad effects upon the properties they control, but because of some merits or demerits attached to the states of the decision variables themselves. For example, in the case of the factory referred to in paragraph 3.12, it might be organisationally or economically more useful to employ certain machines or certain thicknesses of metal rather than others. The fact that different merits are attached to different states of a variable means that the variable is a property within the terms of the definition in paragraph 2.1, and the relationship of different states of the decision variable with different degrees of fulfilment of objective is determined by some arbiter, as described in paragraph 2.29. Thus a decision variable, as well as controlling a property, may itself be a property (fig 3.13).

3.14 The distinctions as to whether an input variable is a decision variable or a context variable, whether or not certain states of a decision variable are accessible to the decision maker, and whether or not a decision variable is also a property, are all part of the definition of the problem rather than part of the problem to be handled. The persons, or bodies of people, or the impersonal forces making these distinctions will also be referred to as arbiters in the problem, as suggested in paragraph 2.29. When an arbiter is beyond reach of any persuasion or modification, he may be regarded as, or referred to as, 'nature'.

3.15 A set of states selected for the decision variables in a particular case constitutes 'a proposal'. In the case of design problems, this may be referred to as 'a design proposal' or 'a design'. If the proposal were to be implemented, the consequence would be a set of states of the properties which might be called 'the outcome'. In the case of design problems, the outcome may be variously described as 'the design' or 'the product' or as 'the properties of the product'. Strictly speaking, the product, as a piece of hardware, does not appear until it has been embodied by the set of goal directed activities to which the problem solving activities relate (see paragraph 2.4). However, since the problem solving activities are conducted with the end product in mind, these distinctions are difficult to make. For the purposes of this argument, the set of states of the decision variables selected by the decision maker will be referred to as 'the design' (or, in the case of non-design problems, 'the proposal') and the set of states of the properties arising from a proposal will be referred to as 'its performance'. The set of degrees of fulfilment of the objectives appropriate to a particular performance will be referred to as 'the merit' of this performance (fig 3.14). This may be expressed in notation as follows:

Marginal ref. 17

Marginal ref. 78

Design i $\longrightarrow$ Performance x $\longrightarrow$ Merit y (where $\longrightarrow$ signifies 'leads to').

$$\text{Design } i = \{D_1(i), D_2(i) \ldots . D_n(i)\}$$

$$\text{Performance } x = \{P_1(x), P_2(x) \ldots . P_n(x)\}$$

$$\text{Merit } y = \{O_1(y), O_2(y) \ldots . O_n(y)\}$$

$\{D_1(i), D_2(i) \ldots . D_n(i)\}$ signifies a set of states i for a set of decision variables $D_1, D_2 \ldots . D_n$.

$\{P_1(x), P_2(x) \ldots . P_n(x)\}$ signifies a set of states x for a set of properties $P_1, P_2 \ldots . P_n$.

$\{O_1(y), O_2(y) \ldots . O_n(y)\}$ signifies a set of states y for a set of objectives $O_1, O_2 \ldots . O_n$.

3.16 Similarly, the set of states of the context variables which apply in a given case constitutes the context of the problem (fig 3.15). It is the combined effects of the proposal and the context which determines the outcome, or performance.

Context k → Performance x → Merit y (where → signifies 'leads to').
Design i →

$$\text{Context } k = \{C_1(k), C_2(k) \dots C_n(k)\}$$

$\{C_1(k), C_2(k) \dots C_n(k)\}$ signifies a set of states k for a set of context variables $C_1, C_2 \dots C_n$.

3.17 The set of criteria against which performance Marginal ref. 75
is measured is described here as 'the performance specification'. A performance specification will lay down the properties which the outcome is required to constitute, and will indicate the way in which various states of these properties will be regarded as being more or less satisfactory. In other words, it lists the properties and defines the goal/property relationships (fig 3.16).

$\{(O_1 = fP_1), (O_2 = fP_2) \dots (O_n = fP_n)\}$ signifies a performance specification relating to properties $P_1, P_2 \dots P_n$.

For example, the performance specification for a chair may lay down that it must accommodate people of a prescribed range of statures and build, withstand certain structural tests, sell at less than a certain price, and earn a profit at a certain rate on investment. The design resource will be the set of materials, processes, shapes finishes, and so on, which the designer has at his discretion. The context will be the characteristics of materials, prices of commodities, and other imponderables which will affect the result, but over which the designer has no control. The design will be the set of decisions (materials, processes, shapes, finishes, etc) that he actually chose. The performance of the design would be range of statures and build of people that the chair (if embodied) would actually accommodate, the tests it would meet, the price at which it would sell, and the profit it would earn. The merit of this performance would be degree to which it approached the ideals indicated in the performance specification.

3.18 It has been pointed out in Section 2 that the co-existence of a number of objectives in a problem defines a certain domain of acceptability. The limiting states of the properties and the laws governing their interrelations were said to define a certain realm of feasibility. The superimposition of the domain of acceptability and the realm of feasibility were described as defining the arena in which an adequate performance must be developed. In a similar way the ranges of limiting values and the laws governing the interrelationships of the decision variables define what may be termed 'the scope' of the design (or decision) resource.

3.19 The description of the nature of the act of designing which was set out in paragraph 2.28 can now be expanded to take in the concept of the goal-decision systems:

1 agreeing objectives
2 identifying the properties or conditions required to be exhibited in the end result
3 determining the relationships between varying states of the properties and the varying degrees of fulfilment of their respective objectives
4 establishing the limiting and ideal states of the properties, and hence the domain of acceptability implied by the objectives
5 identifying the decision variables available to the designer, and the scope of the resources as defined by their limiting states and interrelationships
6 formulating a model of the goal-decision systems present, linking the decision variables with the properties, and the properties with the objectives
7 ensuring that the interdependence of the properties constitutes a realm of feasibility and that this lies at least in part in the domain of acceptability
8 proposing one or more sets of states for the decision variables, within the scope of the resources; establishing the predicted performance(s), that is to say, the resulting sets of states of the properties; and ensuring that at least one performance lies within the arena defined by step 7 above
9 selecting the optimum proposal

3.20 In a particular design problem it may be possible to produce several feasible and acceptable designs. Although it is quite possible for two different designs to exhibit an identical performance, it is more usual for alternative designs to fulfil the given objectives in differing degrees (fig 3.17).

Design j $\longrightarrow$ Performance w $\longrightarrow$ Merit z

$$\text{Design (or proposal) } j = \{D_1(j), D_2(j) \ldots . D_n(j)\}$$

$$\text{Performance } w = \{P_1(w), P_2(w) \ldots . P_n(w)\}$$

$$\text{Merit } z = \{O_1(z), O_2(z) \ldots . O_n(z)\}$$

where $D_n(j)$ signifies an alternative state j of decision variable D_n (state j being an alternative to state i)

3.21 It is also likely that attainment of a satisfactory performance in respect of some objectives will be regarded as more important than the attainment of a satisfactory performance in respect of others. That is to say, the objectives themselves have an order of importance.

In a diagram of performance, the relative merit of alternative designs may be more readily discerned if the objective fulfilment scales are arranged in order of importance and the merits of the individual performances are indicated on them (fig 3.18).

3.22 It is likely that in the case of any two competing designs each will score well in a different set of objectives. In general, a solution which scores well in high ranking objectives is to be preferred over one which scores well only in low ranking objectives.

On the diagram comparison is simplified if the points indicating merit for a particular performance are joined (fig 3.19). Overall merit can be evaluated by comparing the resulting curves.

3.23 In two merit curves, a tendency to lie above is better than a tendency to lie below, since according to the conventions adopted the direction called good always points upwards (fig 3.20).

Similarly, a tendency to a positive slope (northeast to southwest) is better than a tendency to a negative slope (northwest to southeast), since the higher scores should be in the higher ranking objectives (fig 3.21).

Again, a convex curve (intermediate values tending upwards) is better than a concave curve (intermediate values tending downwards) since the intermediate values score better in the convex curve (fig 3.22).

3.24 However, the analysis of these curves is hampered by the fact that in real-world design problems the notional difference in importance between (say) the objective ranked first and the objective ranked second may be regarded by the arbiters as very much greater (or less) than the difference in importance between (say) the objective ranked second and the objective ranked third. Hence a rating scale, such as that employed for the rating of merit in respect of non-quantifiable properties (paragraph 2.16), may also be employed for the rating of importance.

3.25 It is convenient to begin by rating the importance of objectives on a scale of 0-100 (fig 3.23). Thus, in a project with (say) 40 objectives, that objective which is regarded as overwhelmingly the most important might be rated at 100. The next most important at 75 and most of the others between 60 and 50. A very minor objective might be rated at 5. Two or more objectives may take the same rating, where necessary, and the scale may be extended or modified as convenient. Marginal ref. 20

3.26 The comparative evaluation of merit curves, as sought in para. ~~3.23~~ 3.22 then becomes simpler. Each curve is fully described by the location of the points on it, using the convention of co-ordinates. The importance scale becomes the horizontal axis and the merit scale becomes the vertical axis (fig 3.24).

r signifies an importance rating (where r is any factor appropriate)

r_{O_n} signifies the importance rating of objective O_n

$$\left\{\left(r_{O_1}, O_1(y)\right), \left(r_{O_2}, O_2(y)\right) \ldots\ldots \left(r_{O_n}, O_n(y)\right)\right\}$$

signifies the merit curve y for a set of objectives $O_1, O_2 \ldots\ldots O_n$

3.27 An ideal overall performance (fig 3.25) would be one in which each objective is completely fulfiled - that is to say, where $O_1(y)=1$, $O_2(y)=1$ .... $O_n(y)=1$. Hence:

$$\text{curve of ideal performance} = \left\{(r_{O_1}, 1), (r_{O_2}, 1) \ldots\ldots (r_{O_n}, 1)\right\}$$

3.28 The relative merits of the performances of two or more designs may be expressed in terms of their departure from the ideal performance. All the criteria for merit comparison set out in para. 3.23 are satisfied when the overall merit of a design is calculated as the ratio of the sum of the degrees of fulfilment of the individual objectives, each weighted by its importance rating, to the sum of the ideal degree of fulfilment of objectives, weighted by their importance weighting (fig 3.26). Marginal reference 112

$$M_{iy}(t) = \frac{\sum\left(r_{o_n} . O_n(y)\right)}{\sum r_{o_n}}$$

where

M signifies an index of merit

M_{iy} signifies an index of merit M relating to a performance y arising from a proposal i (where i and y are identifying letters or numbers for particular proposals and performances respectively).

$M_{iy}(t)$ signifies a particular value t for an index of merit M_{iy} (where t is a number lying between zero and unity).

In this formulation, overall merit in respect of any given number of objectives is rated on the scale zero-to-unity in exactly the same way as degree of fulfilment of a goal is measured. That is to say, when the index is 1, the performance is ideal; when the index is .5, the merit of the performance is at the threshold between acceptability and unacceptability. The technique of employing this index of merit for the evaluation of performance will be described here as the 'rated-objective merit-index' technique (ro-mi).

3.29 Clearly, the validity of the rated-objective merit-index hangs upon the validity of the importance ratings by which the degrees of fulfilment of individual objectives are weighted. Equally clearly, the importance ratings assigned to objectives are human judgements and prey to all the fallibilities of human judgement. However the presence of human values in a problem is Marginal ref. 19

3.29 (contd)

inherent in the concept of problem solving as a goal directed activity as here defined (see paras 2.1 - 2.6). The mechanism by which value judgements are made, and by which importance ratings are assigned, are dealt with in sections 8 and 6 respectively.

3.30 However, the occurrence of an incorrect assignment of an importance rating at the commencement of a project need not be a disasterous event. It is open to the arbiter or arbiters in a problem to manipulate the importance ratings in any way they wish, and to revise their ratings at any stage they wish, so as to represent their true aims and interests as the consequences of their decisions emerge, or fresh information becomes available.

3.31 Where it is desired that good fulfilment of a lower ranking objective should be capable of outweighing a less good fulfilment of a higher ranking objective, then small intervals may be chosen between their respective ratings. For example:

Where the rank of O_1 is greater than the rank of O_2 but where $r_{o_2} . O_2(y)$ is to be permitted to exceed $r_{o_1} . O_1(y)$

then r_{o_1} might be assigned 100

and r_{o_2} might be assigned 99

Thus, when $O_1(y) = .5$

and $O_2(y) = .6$

then $r_{o_1} . O_1(y) = 50$

and $r_{o_2} . O_2(y) = 59.4$

3.32 Alternatively, where it is desired that even the maximum fulfilment of a lower ranking objective should never be capable of outweighing even the most marginal fulfilment of a higher ranking objective, then large intervals between ratings may be chosen. For example:

3.32 (contd)

Where the rank of O_1 is greater than the rank of O_2 and where $r_{o_2}.O_2(y)$ must not exceed the threshold value of $r_{o_1}.O_1(y)$

then r_{o_1} might be assigned 100

and r_{o_2} might be assigned 50

Thus, when $O_1(y) = .5$

and $O_2(y) = 1$

then $r_{o_1}.O_1(y) = 50$

and $r_{o_2}.O_2(y) = 50$

Marginal ref. 109

3.33 In addition to selecting appropriate importance ratings for the objectives in a project, arbiters must also ensure that the correct values are chosen for the key values of the properties P identified by the objectives, particularly in respect of the limits of acceptability P(l) or P(m). According to the conventions adopted in the ro-mi technique a design is totally unacceptable if it falls below the limit of acceptability in respect of any objective. If, in order to obtain a solution at all, arbiters are compelled to accept a design falling below the threshold previously adopted in respect of a certain objective, the decision to accept the design is equivalent to deciding to shift the level of acceptability in respect of that objective. Marginal ref. 21

3.34 The combination (fig 3.27) of the ro-mi technique thus defined with the systematic model described in para. ~~3.14~~ 3.15 provides a further reformulation of the nature of the design act, thus:

1 agreeing objectives
2 rating objectives
3 identifying the properties required to be exhibited in the end result
4 determining the relationships between the varying states of the property and the varying degrees of fulfilment of their respective objectives
5 establishing the limiting states of the properties and hence the domain of acceptability implied by the objectives

} preparation of a product performance specification

3.34 (contd)

6 identifying the decision variables available to the designer, and the scope of the resources as defined by their limiting states and inter-relationships

7 formulating a model of the goal-decision systems present, linking the decision variables with the properties, and the properties with the objectives

establishment of the design resources

8 ensuring that the interdependence of the properties constitutes a realm of feasibility and that this lies at least in part in the domain of acceptability

9 proposing one or more sets of states for the decision variables, within the scope of the resources; establishing the predicted performance(s), (that is to say, the resulting sets of states of the properties); and ensuring that at least one performance lies within the arena defined by step 8 above

development of design solution(s)

10 evaluating the merit of the predicted overall performance(s)

11 selecting the optimum solution

12 communicating design description

evaluation of design(s)

3.35 The diagrammatic form of the systematic model employed in this argument so far (for example, fig. 3.27) becomes excessively complicated when more than four or five properties are involved. A more flexible model is provided when the variables are displayed in the form of a matrix (fig. 3.28). In the course of formulating a problem and developing a solution the matrix is gradually filled out, in interplay with the real-world situation and with the analogues adopted, as described in section 4. The matrix form lends itself to automatic computation and replication. In the remainder of this text, the diagrammatic form of the systematic model will be retained as a conceptual model, but the matrix form will be regarded as the effective form. Marginal ref. 22

Bibliography 3

* Ackoff, Russell L., Scientific method: optimising applied research decisions, Wiley, 1962.

* Ackoff, Russell L., (editor), Progress in operations research: Vol 1, Wiley, 1961.

* Adams, E., and Messick, S., An axiomatic formulation and generalisation of successive intervals scaling, Psychometrika, 1958, 23, 355-68.

Adler, Irving, The NEW mathematics, John Day, 1958.

Ashby, W. Ross, Introduction to cybernetics, Chapman and Hall, 1957.

Asimow, Morris, Introduction to design, Prentice Hall, 1962.

Boulding, Kenneth E., General systems theory: skeleton of a science, Management Science, April 1956.

Bowen, Hugh M., Rational design 1-7, Industrial Design, February/March/April/May/June/July/August 1964.

* Coombs, Clyde H., Psychological scaling without a unit of measurement, Psychological Review, 57, May 1950, 145-58.

Jones, J. Christopher, (editor), Conference on design methods, Pergamon, 1963.

McCrory, R.J., The design method: a scientific approach to valid design, American Society of Mechanical Engineers, 20 May 1963.

* Miller, David W. and Starr, Martin K., Executive decisions and operations research, Prentice Hall, 1960.

Pask, Gordon, An approach to cybernetics, Hutchinson, 1961.

Starr, Martin K., Product design and decision theory, Prentice Hall, 1963.

* Stevens, S.S., On the theory of scales of measurement, Science 1946, 103, 677-80.

* Tavistock Institute, Interdependence and uncertainty: digest of a report from the Tavistock Institute, Tavistock Publications, 1966.

Wiener, Norbert, Cybernetics, Wiley, 1948.

* already listed in the bibliography of an earlier section

4 The operational model

4.1 They systematic model developed in Section 3 is an effective means for setting out the logical structure of a problem, but it does nothing in itself to establish what the solution might be. That is to say, it is not an operational model. Marginal ref. 69

4.2 In any given system, the ways in which the outputs vary in response to changes in the inputs will be governed by appropriate 'laws'. The corpus of knowledge about such laws constitutes the disciplines of physics, chemistry, mechanics, electronics, economics, sociology, psychology, ethics, aesthetics, etc. The main justification for the employment of specialists (that is to say, of architects, mechanical engineers, electronic engineers, industrial designers, typographers, etc) on different classes of design problem is that the specialist has acquired by training and/or experience knowledge of the principal laws which apply to the kinds of systems which occur most frequently in his area of specialisation. Marginal ref. 80

4.3 Even so, it is frequently difficult to discern the laws operating in a particular case, or, if the general form of the law is known, actually to predict an outcome. A system in which the precise connection between input and output variation is unknown is referred to as a 'black box' (fig 4.1). Marginal ref. 70

4.4 One effective means for determining the effect of various inputs on the output of a black box is to employ as a model another system which is known to behave in a similar way (fig 4.2). For example, scale models of river and tidal basins have been used to predict the silting effects of proposed pier-building operations. Architects' and engineers' drawings are graphical models of the structures they represent. Marginal ref. 23

4.5 Models may also be employed where the laws governing a system are known. The mathematical formulae in engineers' handbooks, for example, are abstract models for predictable systems.

4.6 A model which behaves in a way which is analogous to the way in which a real-world object or system behaves is known as an analogue. No analogue behaves in every way like the real object or system it represents - if it did it would be described as a prototype rather than an analogue. Prototypes are very useful in determining the overall effect of many design decisions. On the other hand, they can be expensive to build and Marginal ref. 24

modify, and may be ineffectual as a means for indicating the possible results of alternative configurations. In general, analogues are selected on the basis of their economy in setting up, and ease of adjustments in exploring alternative solutions. Drawings, nomographs and mathematical formulae make very effective design analogues.

4.7 It has already been observed that the systematic model employed in this argument so far is not an operational analogue, since it cannot of itself produce predictions about the solutions to the problem it represents. However, if the systematic model is used in conjunction with one or more analogues it becomes operational. The designer Marginal ref. 25
can employ the systematic model to represent the logical relationships between the parts of the real-world problem, and also to evaluate the overall effect of the various system outputs, whilst using various analogues to determine the outputs which would result from various design proposals(fig 4.3).

4.8 Because no analogue is complete and perfect, it is usually necessary to employ different analogues for different systems, or for different parts or aspects of a given system, so that typically the overall operational model consists of one or more systematic models with a number of analogues (fig 4.4).

For example, a plan drawing might be employed to determine the layout of the rooms in a building, vector diagrams to work out the distribution of structural loads and a block model to predict overall appearance.

4.9 Since, in terms of the systematic model, some systems receive as inputs the outputs of other systems, it is usually necessary to operate on their respective analogues in sequence.

Sometimes, however, a system of systems may form a closed loop, with every subsystem depending on inputs from another subsystem (fig 4.5). In such cases, it may be desirable to allot trail values to one or more of the input variables, and then to proceed around the cycle, perhaps more than once, adjusting the trial values until mutually acceptable results are obtained.

4.10 Closed loops may enclose the whole or only a part of the systematic model of a real-world problem. In the course of cycling the loop the designer's perception of his real-world problem, his Marginal ref. 26
concept of the design solution grows. In a sense, the design process is thus a dialogue between the real-world and the operational model (fig 4.6).

4.11 On the basis of this operational model, the act of designing can be thought of as comprising a reiterative subroutine applied to different parts of the overall problem in turn, re-cycling where necessary as the problem becomes clearer and as the effects of trial values are discerned.

4.12 In Sections 2 and 3 references have been made to acts of ranking or the assignment of ratings to properties or objectives. The term 'arbiter' has been applied to one who nominates an objective, determines the relationship between states of a property and degree of fulfilment of objective, assigns an importance rating to an objective, distinguishes between those inputs which are to be context variables and those which are to be decision variables, assigns limits to the ranges of states of decision variables available, and decides which (if any) decision variables are also properties. The role of arbiters will be discussed in more detail in Section 5.

4.13 Similarly, the term 'decision maker' has been applied to one who selects values for a decision variable. The role of decision makers will also be discussed further in Section 5.

4.14 A more detailed formulation of the movements of a designer between his problem and the operational model, as defined so far, may therefore be seen (fig 4.7) as follows: Marginal ref. 87

		X-ref. in fig 3.28
1	appraise overall problem in the light of the systematic model and partial solutions (if any), as discerned so far	
2	select the next subproblem most intimately related to subproblems handled so far, or the next most dominant subproblem which promises to yield to analysis	
3	identify the arbiters entitled to nominate objectives in this subproblem	
4	in consultation with the arbiters, identify the objectives in this subproblem	col 1
5	identify the property defined by each objective	col 2
6	by agreement between the arbiters, assign importance ratings to the objectives	col 3

		X-ref. in fig 3.28
7	in consultation with the arbiters, determine the limiting states of the properties which are to be equivalent to the ideal and threshold degrees of fulfilment of their respective objectives	cols 4 & 5
8	establish the relationships (internal or specific laws) connecting varying states of the properties with varying degrees of fulfilment of their respective objectives	col 6
9	establish the domain of acceptability defined by the superimposition of the limiting states of the properties (if necessary, in order to gain a positive domain of acceptability, negotiate changes at 7, and repeat)	cols 4 & 5
10	identify the relationships (external or general laws) governing any interdependence existing between the states of properties identified at 5 above	cols 4 & 5
11	establish the realm of feasibility defined by the compatible ranges of states of the properties (if necessary, in order to obtain a positive realm of feasibility, take an inventive step creating new relationships at 10, and repeat)	cols 4 & 5
12	establish the arena within which a performance must be found, as defined by the superimposition of the domain of acceptability and the realm of feasibility (if necessary, in order to obtain a positive arena for performance, negotiate changes at 7, and/or create new relationships at 10, and repeat)	cols 4 & 5
13	identify the context variables which contribute to governing the goal-decision systems under examination (including those context variables which arise from subproblems already handled)	col 7
14	identify the decision variables governing the states of the properties	col 8
15	erect a (or improve the existing) systematic model of the goal-decision systems connecting the decision variables with the properties, and the properties with the objectives, in the subproblem	

		X-ref. in fig 3.28
16	identify the laws connecting the varying states of the decision variables and context variables (inputs) with the varying states of the properties (outputs) in the goal-decision systems identified at 15	col 9
17	establish the ranges of states of the individual context variables which apply to the case in hand	col 10
18	establish the context defined by the super-imposition of the prevailing states of the context variables	col 10
19	establish the ranges of states available in the individual decision variables	cols 11 & 12
20	identify the laws governing any inter-dependence existing between the states of the decision variables at 14	cols 11 & 12
21	establish the scope of the design resource defined by the compatible ranges of states of the decision variables (if necessary, in order to obtain a positive scope of design resources, negotiate changes at 19, and repeat)	cols 11 & 12
22	erect one or more analogues to represent the laws identified at 10, 16 and 20	
23	identify the decision maker(s) entitled to select states of the decision variables in the subproblem	
24	by agreement amongst the decision makers, and using the analogues erected at 22 for the laws at 20, select a self-compatible set (design i) of states for the decision variables	col 13
25	using the analogues erected at 22 for the laws at 16, determine the resultant set (performance x) of states of the properties	col 14
26	establish whether or not performance x lies within the arena for performance defined at 12 (if not repeat from 24). If no solution is obtainable, create new relationships between the properties at 10 (inventive step), or re-work subproblems giving rise to context variables at 13 (re-appraisal), or negotiate new limiting values for the properties at 7 (re-statement), and repeat)	cols 4 & 5

Bibliography 4

* Ackoff, Russell L., Scientific method: optimising applied research decisions, Wiley, 1962.

* Asimow, Morris, Introduction to design, Prentice Hall, 1962.

Beer, Stafford, Cybernetics and management, English Universities Press, 1959.

Beveridge, W.I., The art of scientific investigation, Heinemann, 1957.

* Bowen, Hugh M., Rational design: 1-7, Industrial Design, February/March/April/May/June/July/August 1964.

Duckworth, Eric, A guide to operational research, Methuen, 1962.

* Jones, J. Christopher, 'A method of systematic design', Conference on design methods, (J. Christopher Jones, editor), Pergamon, 1963.

Latham, R.L., Problem analysis by logical approach, Atomic Weapons Research Establishment, 1965.

* McRory, R.J., The design method: a scientific approach to valid design, American Society of Mechanical Engineers, 20 May 1963.

Matchett, E., The controlled evolution of engineering design, Engineering Designer, February 1965.

* Rittel, Horst, The universe of design, Institute of Urban and Regional Development, University of California, Berkely.

* Starr, Martin K., Product design and decision theory, Prentice Hall, 1963.

5 The design programme

5.1 Although there are exceptions, the great majority of design tasks are carried out by designers on behalf of employers or clients, rather than on their own behalfs. The nomination of some, at least, of the objectives and the acceptance or non-acceptance of some, at least, of the standards of performance then lie within the discretion of the employer or client rather than, or in addition to, the discretion of the designer.

5.2 The community, represented by government and other agencies, have their own intersecting sets of objectives, some of which will impinge upon the design project, and in most circumstances they will impose certain overriding requirements and limitations on the design, mainly through laws, regulations and standards. In the case of products exposed for sale or hire, the user and the community also exercise a form of control through the machinery of the market place. Marginal ref. 27

5.3 Similarly, where the thing designed is constructed, marketed or used in a competitive situation, the actual or potential actions and objectives of competitors will influence decisions made by the designer and/or his employer or client.

5.4 Where the designer is working for an employer or client, not only the product objectives but also the objectives of the design task itself (notably the duration and cost) will be subject to the employer's, professional associations' or governmental bodies control or veto. Here, too, the laws of supply and demand may affect what the employer can ask and what the designer will concede. In any event, the objectives and the limits of acceptability in respect of the design task itself will constitute a formula agreed between the parties concerned. Marginal ref. 81

5.5 A high proportion of the design tasks commissioned or committed to designers are regarded by the clients or employers as investments calculated to offer a given probability of yielding a prescribed return by way of income or capital gain. For example, a developer commissioning an architect to design a building is concerned that there is a high enough probability of the architect's producing within given limits of time and cost a design with a high enough probability of being erected within given limits of construction time and cost, and with a high enough probability of commanding a profitable enough rent or sale price. The person or group who controls the deployment of financial resources in a project, whether the capital is his own or supplied by a backer, will be referred to here as 'the developer'. Marginal ref. 72

5.6 In general, the movement of capital through the money market results in higher yields being demanded on investments to which the higher risks are attached (fig 5.1). Marginal ref. 28

5.7 Hence, where a developer has to raise capital for the conduct of a project, he has much to gain from first putting himself in the position of being able to show evidence of the degree of risk attached to, and the extent of returns expected from, the venture.

5.8 Even where the developer has adequate resources of his own, he will normally put only a given proportion of his capital at high risk, or invest a given proportion of income in new development. If, over a period of time, a developer undertakes a number of projects, he will normally expect some of them to fail. Consequently, those projects which succeed must, in the long run, offset the losses of those which fail. It follows that the average yield on a developer's projects must reflect their actual mean risk.

5.9 In virtually all cases, therefore, a development project will go through an exploratory phase in which feasibility, cost, risk and probable yield are estimated. Usually this exploratory phase is conducted on a limited budget, rounded off with a formal report, sometimes extended to the preparation of sketch designs and/or models and almost always submitted to investment analysis before authority is given for the project to proceed to detailed design stages. Marginal ref. 82

5.10 With certain exceptions, the bulk of the cost of an investment in a design development project resides in the cost of tooling and manufacture, with a lesser but still large investment in marketing. Once the design is completed, but before funds are finally committed in these directions, it is usual for a further study to be made of production and marketing prospects and costs.

5.11 The design act must therefore be seen within the context of a more extensive process which includes the realisation of the design proposals as well as the formulation of them. The overall process will be referred to here as a product development programme.

A product development programme will thus normally contain the following phases, with re-appraisal and the opportunity to withdraw at the end of each phase: Marginal ref. 30

Phase 1	policy formulation
Phase 2	preliminary research
Phase 3	sketch designs
Phase 4	detailed design
Phase 5	prototype construction
Phase 6	marketing appraisal
Phase 7	production design
Phase 8	production planning
Phase 9	tooling
Phase 10	production and sale

5.12 In the light of such a programme the primitive concept of the design activity set out in paragraph 3.33 can be seen to be more an outline for a specific phase than a model of a complete design development project. A design project is, in fact, a sequence of design problems, each aspect of the problem and each component of the product becoming a new design problem, to be resolved in the context of what has been decided so far (fig 5.2). Marginal ref. 83

5.13 Reverting to the operational model of the design process referred to in paragraph 4.7, the design programme may be thought of as co-existing with the systematic model and the analogues, but on a third plane (fig 5.3). Thus the systematic model describes the logical relationships of the parts of the problem, and permits evaluation of predicted performance so far; the analogues, selected according to need, simulate the behaviour of systems in the problem and predict the consequences of postulated decisions; whilst the design programme indicates what should be done next if the information is to become available, and the decisions are to be made, in the right order.

Outside all three is the real world, in which the problem arises, against which the arbiters set their standards and in which the product will eventually be constructed and used.

5.14 The design programme (and indeed the entire product development programme) can be made even more effective as a control over the design and/or product development activity if the conventions of critical path methods are adopted (fig 5.4). According to this convention every activity which must be carried out in order to implement the programme is indicated by an arrow. An activity takes place over time, and maximum and minimum time allowances for that activity can be laid down. Every event which terminates an activity (for example, the declaration "All detail drawings are now completed!" is such an event) is indicated by a box or circle at the end of its associated arrow. An event occurs at an instant Marginal ref. 31

in time, and earliest and latest permissible dates for the event can be laid down. Two or more activities may have to be completed before an event can take place (for example, all the drawings for a project may have to have been printed, and all the schedules and a covering letter may have to have been typed before the event called "All documents now ready for despatch to contractor!" can take place). The 'critical path' is that set of sequential activities which, added together, determines the time span of the whole operation.

5.15 The design process may therefore be thought of as having three main components (fig 5.5):

1 The advance through the project and through time, indicated by the design programme, and accomplished with the aid of various analogues.

2 The branching of the problem into its logical parts, independent of time, indicated by the systematic model.

3 The cyclical movement through the subproblems, occupying man-hours but perhaps co-existing in time, connecting the real world, the systematic model, various analogues and the design programme as described by the reiterative routine set out in para. 4.14.

5.16 The complexity of a problem is partly a function of the number of systems embraced by the problem field and partly a function of richness of interconnection of these systems. Marginal ref. 32

5.17 The boundaries of the problem field mark off both the <u>external</u> context - that is to say, the environment from which emanate uncontrollable variables such as the ruling market prices - and the <u>internal</u> context - that is to say, the elements of construction which exhibit uncontrollable variables such as the physical properties of materials. It is usually an objective to minimise the total work content of a programme (in order to cheapen or shorten it), so that the designer will normally strive to keep the problem field small. Sometimes, however, a context variable will prove to be so restrictive or so uncertain that the designer will extend the problem field in order to gain control over it, increasing the complexity but reducing the intensity of the problem.

5.18 The intensity of a problem is a function of the certainty required in the solution relative to the certainty exhibited by the input variables. Clearly, it is much more difficult to produce a highly predictable result on uncertain data, than to produce a very approximate result on reliable data. It is possible, nevertheless, to develop a design which is relatively insensitive to inaccuracies in the data, or to reduce uncertainty by a carefully graduated development and test programme. Marginal ref. 33

5.19 Examination of case studies indicates that a characteristic programme in the consumer goods and light industrial products field is as follows: Marginal ref. 34

Phase 1 - Policy formulation

establish objectives
lay down outline timetable and budget

Phase 2 - Preliminary research

identify problem boundaries
establish the existing state of the art (library research)
prepare outline performance specification (specification 1)
identify probable critical problem areas

Phase 3 - Feasibility study (sketch designs)

conduct information generating experiments Marginal ref. 89
resolve critical problems
propose outline overall solution(s) (sketch design 1)
estimate work content of phases 4 and 5 and probability of a successful outcome

Phase 4 - Design development

expand performance specification (specification 2)
develop detailed design (design 2)
prepare design documentation

Phase 5 - Prototype development

construct prototype (prototype 1)
evaluate technical performance of prototypes
conduct user trials

Phase 6 - Trading study

appraise market potential Marginal ref. 35
appraise marketing/production problem
revise objectives and budget
finalise performance specification (specification 3)

..t

Phase 7 - Production development

develop a production design (design 3)
execute production design documentation
construct pre-production prototypes (prototype 2)
conduct technical, user and market field-tests

Phase 8 - Production planning

prepare marketing plans
prepare production plans
design jigs and tools

Phase 9 - Tooling

construct jigs and tools
construct trial batch of products off tools (prototype 3)
test trial batch
install marketing machinery and production control

Phase 10 - Production and sale

initiate marketing effort
commence production and sale
feed-back market and user information

5.20 Taking the model Plan of Work published by the Royal Institute of British Architects as a basis, the equivalent programme for a building would be as follows: Marginal ref.29

Stage A - Inception

set up client organisation for briefing
consider requirements
appoint architect

Stage B - Feasibility

carry out study of user requirements
carry out study of site conditions
examine planning, design and cost feasibility

Stage C - Outline proposals

develop brief further
complete study of user requirements
carry out study of technical problems
carry out study of planning, design and cost problems

Stage D - Scheme design

finalise brief
full design of project by architect
preliminary design by engineer
prepare cost plan
prepare full explanatory report
submit proposal for all approvals

Stage E - Detail design

complete designs for every part and component of building
complete cost checking of designs

Stage F - Production information

prepare final production drawings
prepare schedules
prepare specifications

Stage G - Bills of quantities

prepare bills of quantities
prepare tender documents

Stage H - Tender action

despatch tender documents
examine tenders and select tenderers
let contracts
notify unsuccessful tenderers

Stage J - Project planning

arrange effective communications system
agree project programme

Stage K - Operations on site

provide design and construction information
implement construction programme
instal and effect budgetary control
instal and effect quality control

5.20 (contd)

<u>Stage L - Completion</u>
inspect completed construction
specify rectification of defects
make good defects
complete contracts and settle accounts
relinquish possession to owner

<u>Stage M - Feedback</u>
analyse job records
inspect completed building
study building in use

5.22 The advance permitted in a single assignment on a phased programme is generally based on the scale of the investment so far, the expected return on capital to be employed and the probability of attaining it (fig 5.6). As the work proceeds, the certainty of the result improves, the return demanded on the investment diminishes, and hence the ratio of investment to return can be increased. Indeed, the whole product development programme can be characterised as an attempt to attain greater certainty. The main function of design management is to sustain a proper balance between the mounting cost of gaining greater certainty and the diminishing return that the overall investment will yield due to these mounting costs. Marginal ref. 36

Bibliography 5

Archer, L. Bruce, Systematic method for designers, Council of Industrial Design, 1966.

Archer, L. Bruce, 'Design', Handbook of management technology, Gordon Wills and Ronald Yearsley (editors), Heineman, 1967.

* Asimow, Morris, Introduction to design, Prentice Hall, 1962

Battersby, A., Network analysis for planning and scheduling, Macmillan, 1964.

* Beer, Stafford, Cybernetics and management, English Universities Press, 1959.

Hanika, F. de P., New thinking in management, Hutchinson, 1965.

* Bowen, Hugh M., Rational design : 1-7, Industrial Design, Feb/Mar/Apr/May/Jun/Jul/Aug 1964.

* Jones, J. Christopher, 'A method of systematic design', Conference on design methods, (J. Christopher Jones, editor), Pergamon, 1963.

Ledus, Robert, How to launch a new product, Crosby Lockwood, 1966.

Lockyer, K., Critical path analysis, Pitman, 1964.

* McCrory, R. J., The design method : a scientific approach to valid design, American Society of Mechanical Engineers, 20 May 1963.

* McDonough, A. M., Information economics and management systems, McGraw Hill, 1963.

* Matchett, E., The controlled evolution of engineering design, Engineering Designer, Feb. 1965.

National Economic Development Council, Investment appraisal, Her Majesty's Stationery Office, 1967.

National Joint Consultative Committee of Architects, Quantity Surveyors and Builders, A code of procedure for selective tendering, 1965.

National Joint Consultative Committee of Architects, Quantity Surveyors and Builders, Building project management, 1963.

Pessemier, Edgar A., New product decisions : an analytical approach, McGraw Hill, 1966.

Royal Institute of British Architects, Plan of work, 1967.

Schlaifer, R., Probability and statistics for business decisions, McGraw Hill, 1959.

* Starr, Martin K., Product design and decision theory, Prentice Hall, 1963.

* Tavistock Institute, Interdependence and uncertainty : digest of a report from the Tavistock Institute, Tavistock Publications, 1966.

Tybout, Richard (editor), Economics of research and development, Ohio State University Press, 1965.

6 The logic of design procedure

6.1 Two more concepts must be introduced before the structure of the design act as formulated in this thesis can be presented as a whole. These are, firstly, the concept of decomposition, applied to the restructuring of the network of subproblems of which the overall design problem is composed; and secondly, the concept of the theory of games, applied to the relationships between the participants in a product development project.

6.2 It has already been argued (paras. 3.7 and 5.12) that the systems comprising a product development problem may be interconnected. Indeed, it is clear that if a system or group of systems is neither affected by the decisions made in another (or the remaining) systems in the problem field nor affects their outcomes, it can be handled as a completely separate problem (fig. 6.1). For example, in a manufacturing company's rationalisation programme, the redesign of certain of the company's products may go hand in hand with the redisposition of the sales force. Both legs of the programme may be desirable in the realisation of the overall set of objectives. However, it is possible that in the circumstances of the project none of the decisions available within the <u>design</u> resource can have any effect upon the disposition of the sales force, and that none of the decisions available within the <u>sales reorganization</u> resource can have any effect upon product design. They can thus be handled as two separate problems.

This paper is concerned in general only with single problems, and in particular with that class of problem which is concerned with the design of artifacts.

6.3 It has been shown (section 3) that according to the conventions adopted two goal-decision systems are connected when either their respective decision variables or their respective output properties are identical or dependent. In either event a decision affecting one will automatically affect the other, and the outcome of one will relate to the outcome of the other (fig. 6.2). The two systems taken together constitute a larger system.

6.4 Two such compound systems, if linked, form a larger system, and two of these form a yet larger system, and so on in a hierarchy until the whole problem is embraced (fig. 6.3). In a single problem field at least one hierarchy is bound to be assignable. If, in a particular instance, it proves to be impossible to embrace all the systems in one hierarchy, then there must be more than one independent problem present.

6.5 Since, however, all the goal-decision systems in a single problem must be inter-connected, at least remotely, and since some goal-decision systems may be directly related to more than one other, there is frequently considerable ambiguity as to which are the more legitimate or useful pairings and hence which is the more appropriate hierarchy (fig. 6.4).

6.6 Nevertheless, it is usually possible to distinguish groups of goal-decision systems such that the richness of interconnection between the members of the group is greater than the connection between the members of the group and systems outside the group (fig. 6.5).

6.7 Such groups can be taken together to form larger groups, and these compound groups to form still larger groups, until the whole problem is embraced (fig. 6.6). This forms a hierarchy as before, but this time provides an optimum grouping based upon richness of interconnection. The technique for Marginal ref. 38
achieving this hierarchical reconstruction of the overall problem network is known as decomposition.

6.8 If the matrix form of the systematic model is being employed (that is, fig. 3.28) the identity of interacting goal-decision systems is seen where given decision variables occur more than once, (that is, in col. 8), related to different objectives.

If the matrix form of the systematic model is not being employed then an interaction matrix (fig. 6.7) must be prepared before decomposition can begin. Several well-tried computer programs exist for Marginal ref. 39
the automatic decomposition of networks.

6.9 The hierarchical reconstruction of a problem network gives the designer guidance as to the order in which he should tackle the subproblems. He is given clear indications as to which other goal-decision systems affect or are affected by a system in hand (fig 6.8). In most circumstances he is likely to choose to work simultaneously or successively on richly interconnected systems.

6.10 Taking into account the importance attached to different objectives, the designer is likely to begin on that group of goal-decision systems which contains the most important objective, and to move on to the group containing the second most important objective, and so on. The hierarchy shows the direct and indirect connections with other goal-decision systems and the index of merit derived from the systematic model shows the quality of performance so far (fig. 6.9).

6.11 The second of the two concepts to be introduced here is that of the theory of games, as applied to the relationships between the participants in a product development project.

The theory of games is concerned with the strategies which are available to each of the participants in any given game. Its purpose is to derive general principles upon which participants may determine their best course of action at any particular state of play. These principles have been applied to other, logically similar, activities such as the conduct of business enterprises and the prosecution of war. Marginal ref. 40

6.12 In general, the conventions of the theory of games can be used to describe any situation where two or more people engage in a competitive activity. The competitors may be seeking the same or different objectives. Groups of participants may form transitory or enduring coalitions for common ends. A single individual playing a solitary game such as patience or solitaire is described as playing 'against nature' or against the laws of chance. Marginal ref. 88

6.13 An essential feature of all game situations is that each participant must decide on his course of action at various points in play in the light of the past and possible future actions of his fellow players. An important object of game theory is to provide means for determining that strategy which will be optimal no matter what an opponent might do. Marginal ref. 37

6.14 Since most business trading situations are game situations, the product development projects conducted within them are subject to game conditions. Even an apparently non-competitive project such as the design and construction of a bridge or a dam can be considered as a game "against nature".

6.15 The participants in a product development project constitute a coalition formed for the pursuit of common ends (see also para. 2.29). In their role as arbiters, or as representatives of the interests of arbiters, some of the participants nominate objectives, rate objectives, distinguish between context variables and decision variables and determine limits of acceptability. In their roles as decision makers, some select states of the decision variables to form a proposed solution. The combined sets of objectives of the individual participants constitute the set of objectives for the project. The complete set of objectives is only rarely definable at the beginning of the project. Most of them emerge by mutual consent as the project progresses. Marginal ref. 41

6.16 Participants will often have differing sets of goals with some in common, some opposing and some goals to which some of the participants are indifferent. In pursuit of the common purpose some sort of implicit or explicit bargain will be struck by the participants - sinking differences, adjusting standards, supporting one another's views.

6.17 As the game proceeds, a participant may see that things are not turning out as he had expected, and he may modify his goals, exercise persuasion or in extreme cases (if he has the power) veto continuation of the game. For example, the developer may find that the project is likely to demand more expenditure than he is able or willing to incur, or he may find that the market or the profit is not likely to be as large as he had hoped, or a licensing or standard authority may withhold consent. In order to accommodate these conditions in the real-world, any effective design procedure must therefore permit radical reappraisal of the problem at any stage.

6.18 In a sense, the ultimate purchaser or user of the thing designed may be regarded as playing a delayed or hidden hand at the table. At the end of the game, if the product is offered on a free market, he might be in a position to exercise a kind of veto by refusing to buy. Foreseeing the purchaser's ultimate reaction is an important part of the designer's role. Most designers also regard guardianship of the <u>user's</u> interests (especially where the ultimate purchaser is not the ultimate user) as an important part of their ethical responsibility.

6.19 As in most other games, the rules of designing do not provide means for determining who will come to the table or what his motives and skills may be. In a sense, this is a hyper-game - the game of the gods - and the players in the mundane game must accept the circumstances in which they find themselves. One of the first acts in the design and development game is therefore to look around and see who happens to be participating in the project and what respective bargaining positions of each of them are.

6.20 Similarly, the context variables (i.e. variables over which the decision makers have no control) in the product development game are the results of other games going on at the same time. It is a social responsibility of the participants to ensure Marginal ref. 42

6.20 (contd)

that neither the direct effect, that is, properties P, nor the indirect effects, that is, incidental outputs Q, of their activities have serious adverse effects on systems outside the project field (fig 6.10). The pollution of rivers by industrial waste, and the effect on the balance of nature of excessive use of pesticides, are examples of inadequate attention to the effects of Q on systems outside the immediate project fields.

6.21 These considerations - that is to say, the hierarchical structure of the problem, and the game theory structure of the problem solving act - must be taken into account in the conduct of a project. Thus the hierarchical structuring of the problem is reflected in step 2 of the routine described in para. 4.14 ("Select the next most dominant subproblem which promises to yield to analysis"), and the theory of games concept helps to clarify the meaning of step 3 ("Identify arbiters"), step 4 ("Identify objectives"), step 5 ("Rate objectives for importance") and step 9 ("Establish domain of acceptability").

Clearly, the routine set out in para. 4.14 applies to every subproblem at every step of the programme Marginal ref. 87A set out in para. 5.19 (fig. 6.11).

Bibliography 6

Alexander, Christopher, Notes on the synthesis of form, Harvard University Press, 1964.

Cartwright, , and Zander, (editors), Group dynamics : research and theory, Row Petersen, 1962.

* Duckworth, Eric, A guide to operational research, Methuen, 1962

Greene, J. R., and Sisson, R. L., Dynamics management and decision games, Wiley, 1959.

* Hanika, F. de P., New thinking in management, Hutchinson, 1965.

* Luce, R. Duncan, and Raiffa, Howard, Games and decisions, Wiley, 1957.

* Miller, David W., and Starr, Martin K., Executive decisions and operations research, Prentice Hall, 1960.

Simon, H. A., The new science of management decision, Harper, 1960.

* Tavistock Institute, Interdependence and uncertainty : digest of a report from the Tavistock Institute, Tavistock Publications, 1966.

* Vajda, S., An introduction to linear programming and the theory of games, Methuen, 1960.

Williams, J. D., The compleat strategyst, McGraw Hill, 1954.

7 Design factors

7.1 The logical model of design problems presented here has relied so far upon the correct identification of the objectives and goal-decision systems relevant to a particular project by the participants in it. Indeed, it is evident that not even the most elaborate logical model will permit arbiters to abdicate responsibility for formulating objectives and ranking or rating them. To illustrate this, an example can be taken from another goal directed problem solving activity - navigation. Automatic take-off and landing controls are available in some aircraft. So are automatic navigators. It is only a matter of time before it becomes possible to dial a map reference or destination code in order to resolve all the detailed subproblems automatically, and to direct an aircraft, or some other type of vehicle, to any desired point. All the automatic problem solving equipment in the world does not absolve the navigator (acting on behalf of all the other participants) from deciding where the vehicle is to be instructed to go.

7.2 Moreover, in any systematically linked multi- Marginal ref. 43
variable problem, there is almost always more than one correct solution (para. 2.26). Thus, even in respect of a given destination, there will almost always be more than one practicable route by which the traveller could go.

7.3 Wherever a choice exists, preferences based upon a system of values may be exercised. Thus, our traveller may discern that of the practicable routes available to him one is the quickest, one the cheapest, one the safest and one the most picturesque. Whether he will value speed over cost, cost over safety, safety over picturesqueness, etc., will vary from person to person, circumstance to circumstance, and time to time. Individual people may make their choices, some according to well formulated systems of values whilst others may be capricious. Classes of people may exhibit statistically predictable preference
behaviour. A logical model of a problem can do Marginal ref. 84
no more than represent, and an operational model can do no more than predict the consequences of, the choices open to the people involved in the decision-making situation.

7.4 Hence there is nothing in methodology which will substitute for the responsibility of the arbiters in a particular project fromnominating the objectives, identifying the limits of acceptability of the qualities associated with the objectives, and ranking and rating the objectives as they deem appropriate.

7.5 Although it may be possible for a project team to identify and rate all the primary objectives at the outset of a programme, there will be many matters about which the arbiters will be indifferent, or unable to form an opinion, at least at the beginning. Nevertheless, during the course of a project, large numbers of major and minor decisions have to be made, whether any or all of the arbiters feel strongly about them or not. Wherever a decision has to be made, some criterion for a 'good' decision (for the purposes of that project) has to be established. Hence an objective has to be established, sooner or later, in respect of every aspect of every feature of the design and its specification and implementation. The question remains - if the logic and method of decision-making will not absolve the participants from identifying the objectives, and if an objective must be nominated in respect of every feature of a design, how can the participants ensure that every relevant factor is taken into consideration?

7.6 There seem to be four approaches in use by designers - systems analysis, morphological analysis, precedent analysis and empiricism.

Systems analysis techniques range from highly abstracted models of man-machine-environment systems based upon information and control theory, developed by cyberneticists; through models of physical systems based upon observed data, developed by system engineers; to questionnaire frameworks based upon method study, developed by methods and value engineers (fig. 7.1). Marginal ref. 44

Morphological analysis techniques employ classification charts for the cross-association of selected problem elements with alternative solution elements (fig. 7.2). Marginal ref. 45

Precedent analysis ranges from unstructured rumination on personal experience, though the study of recorded case histories, to the employment of check lists of the factors handled in the analysis or execution of similar problems. Marginal ref. 46

Empiricism in design consists in either working up fully detailed drawings and schedules or proceeding to build and test a prototype without abstract analysis, thus encountering the decision points only as they arise from necessity. Marginal ref. 47

7.7 The techniques which have achieved the higher levels of abstraction (e.g. systems analysis) are clearly more flexible than those which depend upon 'learning by doing'. Nevertheless, abstraction will normally depend upon the distillation of principles from observed or experienced cases. In general, therefore, the more abstract techniques are likely to be available in fields where the subproblems (individually, if not in combination) have been frequently handled before, and the more empirical techniques will need to be employed where the problems are new.

7.8 Although sparse, systems models, methods study check lists, morphological charts and case histories exist from which operational cues can be drawn. It is not proposed to reproduce detailed lists and structures here. However, from the arguments already presented, a very general classification for design factors may be drawn.

7.9 If a design is to yield a profit to its promoter, it follows that the thing designed must command a value-in-exchange which is greater than its intrinsic value. That is to say, the product must be worth more to the prospective user than the cost to the producer of the materials, processes and labour which went into its production. Thus a few pennies-worth of china clay pressed out into shapes and glazed to become a dinner service, or a few pounds-worth of steel machined to size and assembled to become a machine tool, are worth more to their purchasers than their cost. The measure of the disparity between cost and value-in-exchange is a measure of the profitability of the design. Marginal ref. 48

7.10 Indeed, it can be argued that, with rare exceptions, the one irreducible quality which a product must have - be it efficient or inefficient, beautiful or ugly, durable or transitory - is a value-in-exchange which is greater than its manufactured and marketed cost. If a design does not have this quality, the capital tied up in its development and production cannot be serviced, the distributor has no motive for offering it and the purchaser has an actual disincentive for buying it.

7.11 Value-in-exchange of a commodity is represented by the price which people are willing to pay for it. It has already been argued (paras. 2.1 and 6.16) that different people attach different values to different things under different circumstances. In general, a prospective purchaser will value a product because of its utility or because of its emotional or Marginal ref. 49

sensual desirability. Except where he has Marginal ref. 85
access to unlimited funds, the cash price which
he is willing to pay is a measure of the value
he places on the possession of the commodity,
relative to his other wants and needs.

7.12 The term 'utility' is used here to imply the Marginal ref. 86
fulfilment of some practical need, such as the
sustenance of food, the earning capacity of a
machine tool, the shelter of a house. Within
limits, the better a product fulfils the
purchaser's need, the more he is usually willing
to pay for it.

7.13 It is a matter of common experience that scarcity Marginal ref. 90
in the face of demand causes prices to rise. The
term 'scarcity' is normally applied to insufficient
supply in response to a demand arising from need.
The same mechanism applies to scarcity in the face
of demand arising from emotional and sensual wants.
Thus the rarity of an antique, the uniqueness of
a curio, the novelty of a toy, the individuality
of a high-fashion dress, are all expressions of a
form of scarcity, and in general the greater the
scarcity the higher the value-in-exchange. For the
purposes of this argument the term 'rarity' will
be applied to all these interpretations of scarcity,
novelty, etc.

7.14 The emotional and sensual wants of a purchaser Marginal ref. 50
embrace both sensual gratification, such as the
appreciation of beauty, music and warmth, and
social gratification, such as status, security and
love. Again, within limits, the greater the
gratification the more the purchaser will be willing
to pay. Many emotional and sensual wants are
actually or historically related to real needs.
The term 'emotivity' can be employed to describe
the quality of supplying emotional or sensual
wants.

7.15 It is also a matter for common observation that in
respect of both utility and emotivity, many
purchasers are prepared to pay more for a product
which is immediately available than for one
which might be available after some delay. This
may be described as the quality of availability.

7.16 If one of the project objectives is to maximise Marginal ref. 91
the value-in-exchange of the project by providing
utility, rarity, emotivity and availability, another
is to minimise the manufactured and marketed cost
(fig 7.3).

Cost resides in the outlay per unit product on materials, labour, processes, transport, sales promotion, research, design, development, plant, premises and the servicing of capital. Minimisation of cost is perceived in the product as the quality of economy of means.

7.17 Thus, in any project required to be commercially viable, the design should tend to increase the product's value-in-exchange by maximising utility, rarity, emotivity and/or availability, and to decrease the product's manufactured and marketed cost by economy of means. The developer's gain is not necessarily the purchaser's loss (that is to say, in game theory terms, product development is not necessarily a zero-sum game). The economic conversion of raw materials into more valuable forms can, in appropriate circumstances, constitute a net gain in wealth to the community as a whole, as well as providing utility for the user and profit for the developer.

7.18 These terms, however, need to be translated into others reflecting the practical disciplines within which the design is accustomed to work. Thus 'maximising utility' refers to the problem of correctly identifying the functions which the product is required to perform and devising the mechanisms or other means by which these functions ~~may~~ best be carried out. To do this effectively, the designer must deal also with problems concerning the ergonomic requirements of the user and the structural and other physical limitations of the materials of construction. (fig. 7.4). Marginal ref. 92

7.19 Economy of means demands that the mechanisms and structures employed should be well-fitted to do their jobs, but without redundance. It also demands that the needs and limiations of the available materials and methods of production should be considered. Similarly, the call on capital for development, production and marketing has to be shrewdly calculated (fig. 7.5).

7.20 The quality of availability reflects not only on the financial, productive and marketing capacity of the developer to get the right number of products to the right places at the right time, but also on the motivational forces which will make a prospective purchaser wish to buy such a product at all, attract him to a particular brand and impel him to buy at once or later (fig. 7.6).

Bibliography 7

Allport, Gordon W., Vernon, Philip E., and Lindzey, Gardner, Study of Values, Houghton Mifflin, 1960.

* Ashby, W. Ross, Introduction to cybernetics, Chapman and Hall, 1957.

Atomic Weapons Research Establishment, Problem analysis by logical approach, AWRE, 1965.

Baines, A., and Haley, K. B., 'Linear programming', Operational research in management, R. T. Eddison, K. Pennycuick and B.H.P. Rivett (editors), English Universities Press, 1963.

Cooper, J. B., and McGaugh, J. L., Integrating principles of social psychology, Schankman, 1963.

Fabrycky, W. J., and Banks, Jerry, Procurement and inventory systems: theory and analysis, Reinhold, 1967.

McCormick, E. J., Human engineering, McGraw Hill, 1957.

Norris, K. W., 'The morphological approach to engineering design', Conference on design methods, Pergamon, 1963.

* Schlaifer, R., Probability and statistics for business decisions, McGraw Hill, 1959.

?

8 The problem of aesthetics

8.1 Aesthetics has been singled out from all the disciplines which affect design for three reasons - firstly, it is often quoted as the factor, or one of the factors, which distinguishes design from other types of problem solving activity; secondly, it is widely regarded as being beyond the reach of rational analysis; and thirdly, it is perhaps the least well developed, in the theoretical or academic sense, of all the disciplines handled by a designer.

8.2 Aesthetics is the art or science of the appreciation of the beautiful. Although commonly associated with appeal to the eye alone, the term is equally applicable to the gratification of the other senses. Thus, the sound of music may be aesthetically pleasing, the feel of slime aesthetically repulsive. So, to some people, is the sight of a man stuffing food into his mouth with his fingers. Behaviour, as well as appearance, can be perceived as beautiful or repellent. Hence good taste and bad taste, in all their manifestations, are the subject matter of aesthetics.

8.3 The application of aesthetics in practice consists mainly in doing things (such as designing furniture) which are calculated to please the senses, and in appraising things (such as selecting a wine) according to their appeal to the senses.

Aesthetic theory may be concerned with finding out what, in general, is pleasing and displeasing, good and bad; or what is pleasing to particular groups or sections of the community; or with how some sensations come to be more pleasurable than others.

8.4 A measure of what is pleasing or displeasing to most people, or to different classes of people, can be determined by the applied experimental psychologist, using market research techniques. However, for a market researcher to say that most people like yellow and do not like brown is not to say that yellow is good and brown is bad, except in the opinion of those people in those circumstances at that time. Marginal ref. 51

8.5 The thorny question of what tastes people ought to have is a matter of ethics.

8.5 (contd)

Questions like 'What do we mean by good?' are of the very essence of ethics or moral philosophy. In fact, one could say that since aesthetics is the study of the appreciation of the beautiful, and since beauty, like truth and goodness, is among the subject of ethics, then aesthetics falls into the general field of ethics. Marginal ref. 93

8.6 Alternatively, one might say that aesthetics falls into two broad divisions - descriptive aesthetics, which deals with the empirical facts about perceivable qualities and the statistics of preferences; and ethical aesthetics, which deals with good taste and bad taste, or appropriateness.

8.7 Descriptive aesthetics, in the tradition of naturel science, seeks to observe and understand the nature of phenomena but passes no judgement upon them. As time goes on, the techniques and knowledge developed by the perception psychologist and biologist make observation surer and bring more and more aspects of aesthetic phenomena into the area of the known, and, within limits, the statistically measurable. Marginal ref. 94

8.8 Ethical aesthetics, on the other hand, does seek to make judgements. Ethical aesthetics is concerned with deciding what is good and what is not so good, so far as the sensual apprehension of phenomena is concerned. It is thus setting greater value on one phenomenon and less on another.

8.9 An essential feature of all value judgements is that they make comparisons. These comparisons may be direct product-to-product evaluations. On the other hand, in a field where a history of critical appraisal has been built up, formalised criteria or standards may emerge by which any new offering may be judged without direct reference to specific counterparts. Marginal ref. 52

8.10 Philosophers can, and do, debate ad nauseam the criteria by which one appraises criteria, but for practical purposes one is usually forced back, sooner or later, on the final arbiter - the 'consensus of informed opinion'. Sometimes 'informed opinion' is synonymous with 'public opinion'. Sometimes it means 'professional opinion'. A great deal of what passes for hard scientific fact is based on a consensus of professional opinion. Just as with scientific hypotheses, aesthetic criteria hold good just as long as they are accepted by the consensus of informed opinion.

8.11 Most stable value judgements are built up like the case law of our courts of justice. Each judgement is based upon precedent. Each decision is added to the collection of judgements, and each added decision changes both the norm or 'centre of gravity' and the field of application of the collection. The next decision is thus made on criteria different from those on which the previous decision was based. In stable conditions, a consistent but gradually adapting standard is reached. Marginal ref. 95

For example, given a new consignment of Burgundy, the question of whether or not it conforms with the accepted alcoholic content for its class is a matter of fact, susceptible to measurement. This is neither an aesthetic nor an ethical matter.

That the 'accepted alcoholic content' is right for this class of Burgundy is something which has grown up on precedent in the manner of case law. This must originally have been a matter of aesthetics, within the limits of practicability. That it may have become embodied in the law for the purpose of tax collection is irrelevant, although the existence of such a law may very well help to stabilise and perpetuate the original aesthetic judgement.

8.12 Whether or not one ought to drink alcoholic beverages is a moral question but not an aesthetic one. Repugnance in the face of the behaviour of the inebriated might be a strictly aesthetic reaction, but objections to alcohol are more often strictly moral. How many people like Burgundy, and how many people think it is wrong to drink alcohol, are matters of fact. Since they are facts about aesthetics and ethics, we have called the science of measuring them descriptive aesthetics and descriptive ethics, respectively. Descriptive aesthetics and descriptive ethics pass no judgements and set no standards, they only measure observable facts.

On the other hand, the question of whether or not the new consignment is to be pronounced a 'good' wine is a proper matter for practical (or ethical) aesthetics, since it concerns a value judgement to be passed by informed opinion. The criteria for judgement, such as colour, bouquet, flavour, body and after-taste, may or may not be systematically applied in passing judgement. In many classes of aesthetic judgements the criteria are not consciously recognised at all. But when, say, a professional wine taster evolves such criteria for the purpose of classifying wines, he is practising descriptive aesthetics. He may

8.12 (contd)

himself hate the taste and disapprove of alcohol, but his task is to apply the test of precedent. The actual ethical aesthetic judgement is performed when the body of informed opinion declares the wine fit or unfit to be added to the collection of good Burgundies. This judgement may be represented by - even predicted by - the tests evolved by the wine taster. But the final judgement is not dependent upon, and sees no immutable truths in, tests evolved by wine tasters.

8.13 Moreover, unless the new consignment is an absolute orthodox, average example, it will have shifted the 'centre of gravity' of the collection (using the phrase in the sense referred to above) in para 8.11 by which the next consignment will be judged. If, for example, it exhibits a somewhat dryer flavour than the norm of the collection so far, and yet is accepted, then either the norm or the tolerance for Burgundy flavour is shifted slightly towards dryness. If its colour is lighter, and yet is accepted, then the norm or the tolerance is moved slightly towards paleness. 'They' decide - whatever the wine tasters may have predicted. But who are 'they' - the body of informed opinion, the trend setters? Each individual says, 'This is a good wine'; and if you ask him why, he replies, 'because it pleases me'. He may or may not enumerate the qualities, such as bouquet and body, which particularly please him, and may or may not indicate that these qualities override the abnormalities of dryness and colour. It is possible to distinguish between 'I happen to like this sample', which is almost whimsical in its arbitrariness, and 'I recognise that this sample conforms well to those criteria which are generally accepted to be the marks of a good wine', which defers to the consensus of opinion. Marginal ref. 53

8.14 Mutative or exploratory behaviour is natural in man, and each individual from time to time finds pleasure in exploring the perimeter of current experience. From time to time he will turn to some offbeat titillation. Imitative behaviour is also natural in man, and there are many who have not the imagination or the opportunity for trail blazing, but who are ready to follow in a new direction once it has been shown to them. So when a mutation occurs in our Burgundy, there are some who will find added pleasure in it and some who will not. There are others who, if they see, will imitate. 'They' are the people who are found to be the most reliable models by those who have not the time, the opportunity or the discriminatory powers to be their own arbiters.

8.15 The essence of aesthetics is choice, the aim is appropriateness, and the criteria are the centre of gravity and the periphery of all the choices made so far. Each man has his own standards and a consciousness of other people's standards. Each makes his own choice. Other people with a similar background may make a similar choice. The designer's special problem is that he must usually foresee the probable future choice of other people, as well as his own.

8.16 Given that aesthetic judgements must be made by people, and that predictions about the judgements which people are likely to make must be based upon a kind of case law, it should be possible to collect data and to carry out analyses of trends and probabilities, using techniques well developed in the natural and social sciences. Any such data must ultimately be translated by the designer into a goal-decision system. That is to say, he must establish which properties, and which different states of a property, will give rise to varying degrees of satisfaction; and he must establish which decision variables, and which different states of a decision variable, will give rise to the desired properties. A primary purpose of this paper is to clarify the logic of these basic relationships.

8.17 Very little is known about the combinations of properties - shape, proportion, colour, texture and so on - which give rise to aesthetic satisfaction. Such work as has been done can hardly be said to have put into the hands of designers either a corpus of knowledge or a set of techniques capable of providing rational aesthetic decisions. In the meanwhile, the only effective 'black box' is the sensibility of a discerning and creative designer in full communion with the life and times of the society which he seeks to serve. Marginal ref. 54

8.18 The question of ethics remains. Not only in connection with aesthetics, but also in connection with other design factors such as reliability, safety and profitability, a designer may well find himself faced with a disparity between what people seem to want and what he thinks they really ought to have. For example, an architect or industrial designer may be urged by his client to produce a design which is 'popular' in style whereas he may feel that pandering to popular tastes cheapens the aesthetic standards of the community. Or again, an engineer might be required by his brief to place greater emphasis on economy of means and less emphasis on factors of safety than he may feel is proper.

In this the designer is neither more nor less responsible to his conscience and to the community as a whole than any other member of the community.

8.19 Clearly, it is important to the self-respect of an individual, and ultimately to the stability of a community, that he should be able to avoid dishonesty. Society depends in the long run upon a reasonable assurance that accountants respect the integrity of figures, lawyers the integrity of the law, doctors the integrity of human life, and designers the integrity of design. However, a citizen consulting a doctor or a lawyer depends upon it that his adviser is dedicating himself to the patient's or client's personal interests. He would be greatly dismayed if he thought that his doctor or lawyer was sacrificing his direct interests on the altar of some scientific or philosophic truth. If he were a manufacturer or a consumer he would be equally dismayed if he thought that his designer was sacrificing his interests on the altar of some aesthetic or technological truth.

8.20 This underlines the distinction between the role and responsibility of the professional worker, dedicated to the service of the community, on the one hand, and that of the pure scientist, fine artist or philosopher, dedicated to the pursuit of truths, on the other. Generally speaking, a man must make up his mind whether he is artist or designer, scientist or engineer, philosopher or lawyer and assign his priorities accordingly.

8.21 Inevitably, there will always be a little of the altruist in the idealist, and vice versa.

It is a weakness of the present system of educating architectural, engineering and industrial designers that so often the pursuit of the ideals of fine art and pure science are presented as the only respectable principles, and the concepts of the pursuit of altruism in social and professional service are so often ignored.

8.22 Ethical (and aesthetic) questions arise in the nomination of objectives for a project, in the ranking or rating of objectives, and in the assignment of limits of acceptability. The weight which is attached to fulfilment of an objective and the level at which minimum acceptability is set will depend upon the attitudes and negotiating strengths of the various participants. It has already been indicated (para. 6.18) that most designers regard guardianship of the ultimate user's interests and of the community's interests, at all levels, as their special ethical responsibility. Little work has been done, however, to assemble any corpus of knowledge on the systems of values extant in the community, or of those actually exercised by designers.

Bibliography 8

Ackoff, Russell L., On a science of ethics, Philosophy and Phenomenological Research, Vol IX (1949), pp. 663-72.

Brand, R.H., Measurement of fabric aesthetics, Textile Research Journal, Vol 34, No 9, September 1964.

Chapanis, A., Garner, W.R., and Morgan, C.T., Applied experimental psychology, Chapman and Hall, 1949.

Churchman, C. West, Prediction and optimal decision, Prentice Hall, 1961.

* Gombrich, E.H., Art and illusion, Phaidon, 1956.

Nowell-Smith, P.H., Ethics, Penguin, 1959.

* Osgood, Charles E., Suci, George J., and Tannenbaum, Percy H., The measurement of meaning, University of Illinois Press, 1957.

9 The problem of imperfect information

9.1 In the problem solving routine set out in paragraph 4.14, the problem solver is required first to identify a system connecting one or more properties P with controlling decision variables D and context variables C, and then to select such values of D as will optimise the provision of properties P. (fig 9.1) It has already been noted (section 4) that the laws which govern the relationship of any given property with its controlling decision and context variables will be defined by the disciplines - physics, mechanics, economics, psychology, etc - within which the particular system lies.

9.2 The range of disciplines over which the designer must have some command has also already been discussed (section 7). Some of these disciplines - for example, mechanics, structures, finance - are concerned wholly or mainly with quantifiable phenomena, and the laws operating within them are well known. Other disciplines - for example, motivation, aesthetics, ergonomics - deal with phenomena which are largely qualitative, and the laws operating within them may be less readily describable.

9.3 Nevertheless, a designer is still required to select values for his decision variables and to predict by calculation or judgement what will be the resultant properties in the outcome. It has been observed (section 4) that in order to be able to do this he will often use operational models. (fig 9.2)

9.4 Although the laws governing qualitative phenomena are less widely understood and the means employed for 'calculating' the outcome of given decisions relation to them are often highly empiric, the means for setting out qualitative relationships in abstract or generalised notation, and for computing the results of decisions, are already moderately well developed in formal logic, Boolean algebra, theory of sets, etc. The difficulty lies more in the lack of tabulated data in the fields of motivation, aesthetics, ergonomics, etc, than in the lack of means for manipulating that data once gathered. The principal distinction between phenomena from the operational point of view is therefore not in their 'qualitative v. quantitative' character but in their 'known v. not known' character.

9.5 Statisticians and cyberneticists distinguish three conditions of information - certainty, risk and uncertainty. Certainty is the condition where Marginal ref. 55

9.5 (contd)

the state of a phenomenon is known and can be relied on to remain fixed or to vary according to some predictable pattern. Risk is the condition where the state of the phenomena is known to lie within a given range, or to be varying over a given range, with a calculable probability of being found at a given state, or within a given zone, at a given time. Uncertainty is the condition where the state of the phenomenon is not known, and the probability of its taking a given value or of being found within a given zone is not known.

Thus, if someone were to spin a coin on a plate he could state with certainty that it would eventually come to rest, predict with known risk that it would show heads, and wonder with uncertainty what might have happened to the coin by that time on the following week.

9.6 In the final analysis, even the apparent certainties of physical laws are only relationships which, it is predicted, will continue to prevail over the not too distant future, with a very small risk of being proved wrong, whilst the apparent uncertainties of human whim are really phenomena which can be predicted only with a very high probability of being wrong, so that strictly speaking, certainty and uncertainty are really no more than the extreme cases of a range of degrees of risk (fig 9.3).

9.7 In a problem solving situation, a system in which a prediction about an outcome can be made in conditions of certainty may be described as a deterministic system; a system in which a pre- Marginal ref. 56
diction can be made in conditions of risk may be described as a probabilistic system; and one in which no prediction can be made may be described as a capricious system.

Thus, amongst functional, mechanical and structural problems in particular, a designer will find himself dealing with deterministic systems - that is to say, with systems where the selection of a particular state for the decision variables will reliably result in a given state of the related property defined by the objective. Amongst pro- Marginal ref. 96
duction, marketing and ergonomic problems in particular, he will find himself dealing with probabilistic systems - that is to say, with systems where the selection of a particular state for the decision variables will result in a calculable statistical probability of the state of the property being found at a given point or within a given range.

9.7 (contd)

Amongst motivational and aesthetic problems - in the present state of knowledge - he will encounter capricious systems where he has no calculable assurance that a particular decision will produce a given result.

As the state of human knowledge progresses, more and more systems which have hitherto been regarded as capricious become probabilistic, and as the degree of human control over phenomena increases (in particular, of control over the quality of materials and processes), more and more systems which have hitherto been probabilistic become deterministic.

9.8 In addition to having to discern the laws connecting the decision variables, context variables and output properties in a goal-decision system (or choosing to regard the systems as 'black boxes' and establishing the outcome by means of trial and error in operational models), the designer must collect or generate the data he needs, especially concerning the context variables.

9.9 Unfortunately, very commonly, the data is difficult to find, and when found it very often contains redundancies, errors and omissions. Stemming from the early days of information theory, which was then concerned mainly with the quality of transmission of sound over a telegraph line or a radio carrier frequency, the term 'noisy' is applied to information which is overlaid with redundancies and errors. Signals which contain neither noise nor omissions are called 'perfect' information. Thus data can be perfect, noisy or incomplete. Marginal ref. 57

9.10 Some data will have been gathered, tabulated or classified, and stored awaiting retrieval and use. Examples of this kind of data are seen in architects' and engineers' handbooks, manufacturers' catalogues, research reports and case studies. Other data will be obtainable readily enough, but not having been gathered before, must be sought out in the field and recorded. Examples of this are seen in site surveys, market research and anthropometric studies. Yet other data are not available at all, and must be generated by experiment. Examples of this are seen in test marketing, destruction testing and stress analysis. Some such data can only be generated retrospectively. Almost any combination of deterministic, probabilistic or capricious; noisy, perfect or incomplete; and retrievable, surveyable or generatable information may be found in a design problem.

9.11 According to information theory, the information content of a signal is proportional to the degree to which it narrows the field of remaining uncertainty. For example, the discovery that a component in a design needs to be electrically insulating immediately narrows the field of choice of materials from which it can be made. If it also needs to be heat-resisting, this narrows the field again. The unit of information content is the 'bit', or binary unit of information, and is defined as that which halves the uncertainty. Marginal ref. 58

9.12 The purpose of a design project is to identify the requirements of a product and to describe a design calculated to meet those requirements. Every piece of data gathered, and every decision made, contributes to reducing uncertainty about the nature and effectiveness of the end product. (fig 9.4). The measure of efficiency of the design act is thus the measure of the information content of the data employed and the decisions made. Any time, effort or other resources expended in the design act which does not reduce uncertainty about the requirements, nature and/or effectiveness of the end product is wasted. Marginal ref. 97

9.13 In the majority of cases the cost of the resources devoted to design and development must be added to the selling price of the product or set off against the profit arising from the sale of the product. There is therefore considerable pressure to keep the cost per unit product of the design and development programme as low as reasonably possible. This may be achieved by curtailing the design and development effort so that a greater or lesser degree of residual uncertainty remains about the requirements for or effectiveness of the product when it finally goes on to the market; by spreading the cost of design and development over the maximum number of products; or by increasing the efficiency (i.e. information content) of the design and development activity itself. Marginal ref. 101

9.14 Going into production with residual uncertainty - that is to say, taking a gamble - may well result in higher profits and quicker returns if it succeeds. There is also a higher risk of total loss. Paying the price of making sure, or spreading the cost of a more elaborate design and development programme over a larger number of products, generally result in greater certainty of a smaller profit and with delayed returns. Marginal ref. 98

9.15 It is characteristic of the mechanism of the money market that capital tends to flow to the lower risk investments. The laws of supply and demand apply to capital as much as to anything else. Hence investors jostling for the security of low risk enterprises have to be content with low interest rates and investors adventuring in high risk enterprises demand high interest rates. All investment is a gamble, of course, and is based upon the assumption that the performance of the management concerned will continue in the future to be rather like his overall performance in the past. Hence any new management tends to be regarded as involved in a high risk enterprise, and any capital invested tends to be provided in the expectation of ultimate high returns if the enterprise should succeed. The rate of return which would have to be offered in order to a tendency for capital to flow into a project is described as the marginal cost of financing it. Marginal ref. 59

9.16 Whether a design and development project is financed by bank or other institutional loans, or by public investment, or by the allocation of existing resources, the return required must in the long run reflect the risk of the enterprise. If it does not, capital will tend to flow in or out until the laws of supply and demand force the interest rates up or down.

Where a high risk enterprise is undertaken on a developer's existing resources, he will tend to limit his investment to a given fraction of his total resources, so that a total loss would not unduly affect his overall return. In all cases, therefore, there is a direct relationship between the residual uncertainty at the end of a design and development project and the cost of servicing the capital resources employed (fig 9.5) Marginal ref. 99

9.17 Since, on the other hand, the cost of achieving greater certainty is itself a call on resources, it is clear that the design and development activity must be conducted on such a scale or with such efficiency that the justifiable cost (appropriate to risk) of servicing capital plus the cost of design and development is equal to or less than the margin between the selling price and the manufactured and marketed cost (fig 9.6).

9.18 It has already been argued (paragraph 9.12) that all expenditure of resources on design and development must contribute to the reduction of uncertainty about the properties required to be exhibited in the end result, and the degree to which these properties are, in fact, provided by the design. Where the systems relating to these properties are probabilistic systems, the design and development activity can only determine the statistical probability with which the property will be found, or will be found within a given range, in the end result. The probability with which an overall end result will be found containing simultaneously the required properties in two probabilistic systems is the product of their respective probabilities. For example, if a coin is tossed, there is a .5 probability of its coming down heads. If two coins are tossed, there are four possibilities - two heads, one head one tail, one tail one head, two tails - or a probability of .5x.5 = .25 of their coming down two heads. The expediency of proceeding with a given proposal, in the light of its overall uncertainty, may therefore be expressed as: Marginal ref. 60

$$P_{E_i}(x) = \frac{R_i}{F_i} - \frac{1}{\Theta\{P_n(x)\}}$$ Marginal ref. 100

where

P_{E_i} signifies the index of expediency P_E of proceeding with proposal i

$P_{E_i}(x)$ signifies a particular value x for the index of expediency P_E

R_i signifies the expected return per cent on the capital employed, if proposal i were to be successful

F_i signifies the marginal cost per cent of servicing the capital employed, if proposal i were to be proceeded with

Θ signifies the index of probability

$\Theta\{P_n(x)\}$ signifies the overall probability that the properties P_n will take up the states x predicted (that is, that proposal i will be successful)

A negative value for $P_{E_i}(x)$ would suggest that the proposal is not worth proceeding with, since the expected return is less than that associated with the degree of risk involved.

9.19 In many cases the expected return R_i on the capital employed in a project will reflect the merit of the design in other respects.

$$R_i = fM_{iy}(t)$$

It might therefore be necessary first to establish the predicted quality of the solution apart from its merits as a capital investment, and then to re-calculate its overall merit, taking into account its financial expediency in the light of its other merits. Normally, the relative importance of the financial and other considerations will have been taken into account in assigning importance ratings to objectives:

$$M_{iy_2}(t_2) = \frac{\sum\left(r_{o_n} \cdot O_n(y)\right) + \left(r_{P_{E_i}} \cdot P_{E_i}(x)\right)}{\sum r_{o_n} + r_{P_{E_i}}}$$

where

$M_{iy_2}(t_2)$ signifies the state t_2 of the index of merit M associated with performance y_2 of proposal i, taking into account its expediency P_{E_i}.

$r_{P_{E_i}}$ signifies the weighting to be given to the index of expediency P_{E_i}.

9.20 A technique for setting out the possible outcomes of alternative courses of action (in this case, of alternative designs and/or of alternative levels of research, design and development effort) is known as the pay-off matrix (fig 9.7). The merit of each alternative proposal under each of the sets of circumstances which might then prevail is set out, so that a selection can be made. In most research, design and development projects, a reappraisal of this sort (whether formally set out or not) is usually made at the end of each stage of the project programme (fig 9.8).

Marginal ref. 102

9.21 It can be concluded that every effort should be made to avoid dependence on capricious systems, or systems with high uncertainty. Probabilistic systems are better than capricious systems and deterministic systems are better than probabilistic systems, so far as the efficiency of the design act is concerned. For a particular set of phenomena to constitute a deterministic or probabilistic system, there must be laws connecting inputs with outputs. The discernment of such laws from examination of case studies, tabulated data and experiment is an important function of design research.

9.22 It can also be concluded that retrievable (i.e. already tabulated) information is generally better than surveyable or generatable information, on grounds of cost. Perfect information is obviously better than noisy or incomplete information. This again emphasises the importance of recording full and accurate case study data.

9.23 There are three things which a designer can do to ease his task. He can strive to see that the project objectives define as large an arena for performance as possible, he can try to produce as flexible a solution as possible, or he can make simplifying assumptions.

A large arena for performance means that the designer is not so closely hemmed in by constraints that success in fulfilment of one objective is achieved only at the cost of marginal fulfilment of another, and a flexible solution is one which will accommodate to unexpected variations in input or output data. Taken together these can be described as creating conditions where a 'loose fit' between design and requirements can occur without detriment.

The technique of making plausible simplifying assumptions in the face of non-deterministic systems or noisy data can greatly speed progress in the solution of a complex problem provided that care is taken to validate experimentally any assumption that promises to be critical to the validity of the solution as a whole. The advantage of making assumptions rather than testing all available states resides in the fact that once a solution has been found it is only necessary to prove that the assumed value is valid, instead of establishing that a certain range of states would be equally or variably valid. The employment of operational models (section 4) is frequently associated with the solution of problems based upon assumption and test.

Bibliography 9

* Ackoff, Russell L., Scientific method: optimising applied research decisions, Wiley, 1962.

* Beer, Stafford, Cybernetics and management, English Universities Press, 1959.

Cherry, Colin, On human communications, Chapman and Hall, 1957.

Good, I.J., Rational decisions, Journal of the Royal Statistical Society, B, Vol 14, 1952.

Merrett, A.J., and Sykes, Allen, The finance and analysis of capital projects, Longmans, 1963.

* Miller, David W., and Starr, Martin K., Executive decisions and operations research, Prentice Hall, 1960.

* National Economic Development Council, Investment appraisal, Her Majesty's Stationery Office, 1967.

Rittel, Horst, 'Hierarchy or team?', Economics of research and development, Richard A. Tybout (editor), Ohio State University Press, 1965.

* Schlaifer, R., Probability and statistics for business decisions, McGraw Hill, 1959.

* Starr, Martin K., Product design and decision theory, Prentice Hall, 1963.

* Tavistock Institute, Interdependence and uncertainty: digest of a report from the Tavistock Institute, Tavistock Publications, 1966.

10 Techniques in problem solving

10.1 Traditionally, the designer has worked largely intuitively - studying his brief, scanning the evidence, ruminating upon implications and sketching ideas without the exercise of very much conscious control over the activity of design decision making itself, or very much conscious reasoning in arriving at decisions. In many classes of design problem this procedure has been, and is likely to remain, entirely adequate. In textile, clothing, jewellery, some ceramics, much interior and most furniture design, for example, it would seem that circumstances would seldom warrant the expenditure of much time and effort on justifying, intellectually, propositions which can be very rapidly tested in practice.

10.2 There are some areas, however, where it is becoming less and less possible to depend wholly upon intuition in choosing a route through the problem or in making design decisions. For example, the design of complex buildings such as hospitals involves such a very large number of interacting variables and requires so many detailed subproblem solutions that the architect cannot trust to intuition to tell him which is the best order in which to deal with them or whether he has covered all the ground. Similarly, there are some mechanical and systems engineering problems (not always relating to big or complex structures) which involve such complex overlays of the areas of acceptability in objectives, and such limited intersections of the curves of feasibility, that the chances of selecting intuitively a design idea which will turn out to be both feasible and acceptable are very remote.

The increasing standards of performance being demanded of designs, and the increasing variety of materials and processes becoming available to construct them with, are tending to increase the frequency with which such difficult cases arise.

10.3 There is evidence, moreover, that even where problems are to be handled intuitively, a designer (or other problem solver) is better able to ruminate on his particular problem when he is in possession of 'structural' concepts of the logic of the general class of problems into which his problem falls and of the general programme of events through which his activity is likely to pass than when he has no such structural concept. Marginal ref. 61

10.4 It is important to distinguish between technique and policy. A problem solver may choose to follow a policy of planning (which is defined as the policy of intelligently anticipating how an objective can be achieved) or one of expediency (which is defined as the policy Marginal ref 103

10.4 (contd)

of being guided by needs of the moment). Whichever he chooses, as he comes to each decision point, he can employ the technique of rational decision making (which is defined as trying to reach a conclusion on the basis of reasoning from premises by connected thought) or the technique of intuition (which is defined as reaching a conclusion by insight or assertion).

10.5 It is also important to distinguish between the manner of forming an intent and the manner of pursuing it. The objectives in a design project may be selected by reasoning or intuition. The standards set may be high or low. But however they are arrived at, questions as to the merits and demerits of the objectives and standards selected must rest ultimately on question as to the value systems of the people involved or of the society in which they operate. Some such questions stand beyond the reach of analytical reasoning. Marginal ref. 104

10.6 The pursuit of these objectives, on the other hand, can always be evaluated as efficient or inefficient (in terms of economy in the employment of time and money in problem solving), effective or ineffective (in terms of degree of fulfilment of the objectives), and safe or risky (in terms of probability of the proposed solution's turning out in the event to be as effective as prescribed).

10.7 Thus the polarities of reason v intuition occur at all three levels - in the selection and ranking of objectives, in the organisation of the design activity and in the making of solution decisions. All combinations and degrees of these polarities are found in design practice.

10.8 In general, careful reasoning at any or all levels tends to slow down the design activity and make it more costly, especially during the earlier stages. On the other hand, it also tends to diminish risk.

Intuitive methods are therefore appropriate where the risk and/or consequences of failure are acceptably low, and rational methods are appropriate where risk and/or penalties are high and must be minimised.

10.9 The principles developed in this thesis are intended to apply to both intuitive and rational methods, and at all three levels of design planning and execution. The techniques and terminology presented are intended to be compatible with the neighbouring disciplines of cybernetics, management science, operational research and system

10.9 (contd)

engineering. Indeed, the argument set out here can be categorised as the application of these disciplines to the design activity.

10.10 Although some of the techniques are far from fully developed, there is at least a principle, established in management science, operational research or conventional design practice, which can be applied to each of the steps in the design process described in section 6 (fig. 10.1). It remains, therefore, to accumulate sufficient case study material on the application of these techniques to design problems in order to provide a valid design science.

10.11 It has been repeatedly argued here that the exercise of value judgements in the nomination and rating of objectives is and must remain a human responsibility outside the logic of the problem itself. The development of automatic problem solving techniques would not, therefore, affect the importance or human control of value systems. Indeed, they might well cause the exercise of value judgement to become a vastly more important part of the designer's role.

10.12 The other area where the role of the designer has hitherto been regarded as vital is in the creative act of conceiving design ideas or solutions-in-principle. Given adequate data, however, it is possible, at least in principle, to employ automatic search techniques for finding feasible and/or optimal solutions within the problem constraints. This is particularly practicable in the case of probabilistic and deterministic systems - that is to say, in problems where the laws governing the relationships between decision variables and output properties are known or capable of imitation by models.

10.13 Even in the case of capricious systems - that is to say, in problems where no laws can be discerned in the connection between the decision variables and the outcomes - it is at least theoretically possible to generate random decisions automatically, to build prototypes of the system and to compare outcomes until an acceptable solution is reached.

10.14 The capacity to postulate new ideas is therefore not an indispensible part of the human role, although in the present state of the art and science of design it is an extremely effective one.

10.15 The basis of the effectiveness of human creativity Marginal ref 106
is the capacity of the human brain to provide cheap and subtle (though inaccurate) operational models by which the more promising ideas can be quickly sorted from the less promising ideas.

10.16 For maximum efficiency, a design programme would be conducted with a mixture of rational and intuitive techniques appropriate to the nature of the objectives, the quality of the data, the character of the problems and the certainty required in the end result.

It cannot be emphasised too strongly that this paper is not advocating the slavish pursuit of the principles and routines set out here, in the manner of a step-by-step recipe for designing. On the contrary, the matters contained here are seen as providing, at best, the same sort of guidance as that provided by semantics, accidence, syntax and the principles of composition for the preparation of literary works. In other words, they are an attempt to make explicit the practices which discerning people seem to be adopting.

Bibliography 10

* Beer, Stafford, Cybernetics and management, English Universities Press, 1959.

* Beveridge, W.I., The art of scientific investigation, Heinemann, 1957.

* Churchman, C. West, Prediction and optimal decision, Prentice Hall, 1961.

* Jones, J. Christopher, 'A method of systematic design', Conference on design methods, J. Christopher Jones (editor), Pergamon, 1963.

Massachusetts Institute of Technology, List of idea spurring questions, Creative Education Foundation.

* Matchett, E., The controlled evolution of engineering design, Engineering Designer, February 1965.

* Pask, Gordon, An approach to cybernetics, Hutchinson, 1961.

University of Chicago Psychology Department, List of idea spurring questions, Creative Education Foundation.

Institution of Production Engineers, Computers and production control, 1961.

Vervalin, Charles H., Just what is creativity, Hydrocarbon Processing and Petroleum Refiner, Vol 41, No 10, October 1962, pp. 110-111.

11 Summary and conclusions

11.1 The arguments and hypotheses set out in this thesis are based upon the observation and analysis of a number of case studies, listed in the Appendix. Concepts developed in neighbouring disciplines have been employed to illuminate the nature of the design activity. It is concluded that design is a specific example of a general pattern of problem-solving behaviour.

11.2 All problem-solving activities are goal-directed. The correct identification of the goals, as well as the discovery of means for attaining them, is an essential part of the activity.

11.3 Most design problem-solving activities are carried out within the framework of larger endeavours, and some, at least, of the objectives of the design problems reflect the goals of the encompassing problems.

11.4 More than one person or body of persons may be in a position to nominate the objectives of a design problem, and more than one person or body of persons may be empowered to contribute decisions in its solution. The group of people so empowered constitute a coalition formed for the pursuit of common, allied - or even, in part, opposed - ends. In such a situation the procedure is a dynamic one, where each decision is made, and any objective may be reviewed, by common consent, according to the aims and bargaining powers of the participants.

11.5 Many design problem solving activities are carried out in opposition to competitors. It can be argued that in the absence of human competitors, a project is conducted 'against nature'. In every case, therefore, the design activity is dynamic and spread over time, each decision being taken in the light of the actual or potential counteractions open to competitors.

11.6 Within this framework, a design problem is defined as follows:

11.6 (contd)

Given (by the arbiter(s))

A set of properties which are required to be exhibited in the end result; a specification of the ways in which varying states of the various properties will be regarded as providing varying degrees of satisfaction, including any limits to the acceptable ranges of states of the properties; a specification of the relative importance which is attached to the satisfaction of the various requirements; the set of decision variables which are to be accessible to the decision maker(s), and which govern or partly govern the states of the properties; the limits to the ranges of states of the decision variables which are to be open to the discretion of the decision maker(s); and the set of context variables which are NOT to be at the discretion of the decision maker(s), but which partly govern the states of the properties:

It is required (of the decision maker(s)) to select a set of states of the decision variables such that the satisfaction of the requirements, weighted according to their importance, is optimised:

Provided that the states selected for the decision variables are mutually compatible; the states selected for the decision variables lie within their respective limits of discretion; the laws governing the relationships between decision variables, context variables and properties are complied with; the resultant states of the properties are mutually compatible; and that none of the states of the properties lies outside their respective limits of acceptability.

11.7 The function of conceiving solution hypotheses, or design ideas, has hitherto been regarded as the principal 'human' contribution to designing. Advanced automatic data processing techniques, however, offer the possibility of exploring mechanically all the feasible combinations of values for given decision variables. Creativity in this sense might well, therefore, become a less valuable human facility as time goes on.

11.8 The functions of nominating objectives and rating them for importance remain essentially human and largely subjective. Social science techniques can be employed to discover the value systems of individuals or classes of people, and logical tools can be employed to compute with the data obtained, but

11.8 (contd)

these are only means for making explicit the human and subjective value judgements about goals, which must be made by the people concerned. Perceptiveness in discerning worthwhile objectives, and judgement in rating them for importance, might well become more valuable a human facility as time goes on.

A major deficiency in the present state of the art of designing is the almost complete lack of data on the value systems extant in the community, or employed in design practice.

11.9 Techniques for the handling of all the phases of design exist, at least in principle, within the disciplines of management science, operational research and the various branches of technology. An essential part of the designer's skill is to be acquainted with these disciplines and to be able to discern which techniques are appropriate to what phase.

A second major deficiency in the present state of the art of designing is the almost complete lack of case study evidence as to the techniques employed, and the degree to which each has been found effective, in various classes of design problem.

11.10 The laws connecting the decision variables, context variables and output properties in a particular design problem constitute the disciplines of physics, mechanics, structures, production engineering, economics, marketing, aesthetics, ergonomics etc., appropriate to it. Some of these disciplines are highly developed and some are not.

The third major deficiency in the present state of the art of designing is the paucity of tabulated data, based upon case studies, from which general laws might be distilled in those disciplines which are underdeveloped.

11.11 The structure of the design process, as conceived in this thesis, may be summarised by the following definitions:

1 A PROPERTY
is an attribute, quality or condition in man's environment. A property may take two or more states.

11.11 (contd)

P	signifies a property
P_n	signifies a particular property (where n is an identifying letter or number)
$P_n(x)$	signifies a particular state x of property P_n (where x is either an identifying letter or number, or a value for property P_n according to some appropriate scale).

Certain properties may, in a particular case, co-exist with other properties and may be in some interdependent relationship with them.

$P_1 = fP_2$ (where f signifies some given relationship with, or function of, P_2).

2 <u>A GOAL</u>
is a state of satisfaction in a person or a body of people with <u>a property</u> or a particular state of <u>a property</u>.

O	signifies a goal
O_n	signifies a particular goal (where n is an identifying letter or number)
$O_n(y)$	signifies a degree of fulfillment y of goal O_n on the scale zero-to-unity (where, when the goal is completely fulfilled, then $y = 1$; when the goal is partly fulfilled yet remaining within the limits of acceptability, then $1 > y > .5$; when the fulfillment of the goal is at the threshold between acceptability and non-acceptability, then $y = .5$; and when the degree of fulfillment of the goal is below the threshold of acceptability, then $y < .5$).

Varying degrees of fulfillment of the goal may be associated with varying states of <u>the property</u>.

$P_n(l)$ or $P_n(m)$ signify threshold states l or m of property P_n (that is to say, they are states of P_n associated with $O_n(y) = .5$).

$P_n(u)$ signifies the ideal state u of property P_n (that is to say, a state of P_n associated with $O_n(y) = 1$).

The association between the degrees of fulfilment of a goal and the varying states of a property may be expressible in the form of a law (see fig 11.1).

$O_n = fP_n$ (where f signifies some given relationship with, or function of, P_n).

3 THE RATING
of a goal is the weighting to be applied to the degree of fulfilment of the goal when calculating its contribution to the overall fulfilment of a set of goals.

r_{O_n} signifies the rating r of goal O_n (where r is any appropriate factor).

4 A GOAL DIRECTED ACTIVITY
is action undertaken for the purpose of achieving fulfilment of a goal or a set of goals.

5 A PROBLEM
is a condition where the identity of a property, the law connecting a property with its associated goal, the rating of a goal or the nature of the action to be taken in a goal directed activity is not apparent or is open to choice.

A problem is itself a property, one of whose states is the unresolved condition and the other of whose states is the resolved condition.

6 A PROBLEM SOLVING ACTIVITY
is a goal directed activity in which the goal is to achieve the resolved condition of a problem.

7 AN OBJECTIVE
is the goal of a problem solving activity. This term is employed to assist in distinguishing between an immediately desired condition (the resolved condition of the problem) and an ultimately desired condition (the most acceptable achievable state of the property associated with the goal of the goal directed activity to which the problem solving activity relates).

O signifies an objective. The notation for objectives is identical with that for goals.

8 A DESIGN ACTIVITY
is a problem solving activity in which the objective(s) relate to the means for providing the properties of some artifact or aggregation of artifacts.

11.11 (contd)

9 A DECISION MAKER
is a person or a body of people who conducts a problem solving activity

10 A DESIGNER
is a decision maker in a design activity

11 A DECISION VARIABLE
is a condition which governs or contributes to governing the state taken up by a property and over which the decision maker(s) in a problem solving activity are entitled to exercise control. A decision variable may take two or more states.

D signifies a decision variable

D_n signifies a particular decision variable (where n is an identifying letter or number).

$D_n(i)$ signifies a particular state i chosen for decision variable D_n (where i is either an identifying letter or number, or a value for decision variable D_n according to some appropriate scale).

Varying states of the decision variable may be associated with varying states of its dependent property. The relationship between states of the decision variable and states of the property may be expressible in the form of a law.

$P_n = fD_n$ (where f signifies some given relationship with, or function of, D_n)

The range of states of a decision variable accessible to the discretion of the decision maker(s) may be limited.

$D_n(g)$ and $D_n(h)$ signify limiting states g and h respectively of decision variable D_n in the range of accessible states of D_n (where g and h are identifying letters or numbers, or values according to some appropriate scale).

Amongst the states of the decision variable accessible to the decision maker(s) there may

11.11 (contd)

be some states which are more desirable and other states which are less desirable, NOT because of their effects upon the property controlled by that decision variable, but because of certain merits or demerits attached to the states of the decision variable itself. The apprehension of comparative merits in different states of a decision variable implies that it is itself the subject of a goal, and under these circumstances the decision variable is, at the same time, a property and a factor governing a property.

$P_1 = fD_1$ (where f signifies some given relationship with, or function of, D_1).

$D_1 \equiv P_2$ (where $\equiv$ signifies 'is identical with').

In addition, in a given problem, one decision variable may co-exist with other decision variables, and may have some sort of interdependent relationship with one or more of them. ie $D_n = f D_m$ $m \neq n$

$D_1 = fD_2$ (where f signifies some given relationship with, or function of, D_2).

12 A CONTEXT VARIABLE
is a condition which contributes to governing the state taken up by a property and over which the decision maker(s) in a problem solving activity CANNOT exercise control. A context variable may take one or more states.

C	signifies a context variable
C_n	signifies a particular context variable (where n is an identifying letter or number)
$C_n(k)$	signifies a particular state k of context variable C_n (where k is either an identifying letter or number, or a value for C_n according to some appropriate scale).

11.11 (contd)

Varying states of the context variable, in conjunction with varying states of a decision variable, may be associated with varying states of the dependent property. The relationship between states of the context variable, states of the decision variable and states of the property may be expressible in the form of a law.

$P_n = f(C_n, D_n)$ (where f signifies some relationship with, or function of, C_n and D_n).

13 AN ARBITER
in a goal directed activity is a person, a body of people or a condition in nature who nominates a property; determines the law which is to connect varying states of the property with varying degrees of fulfillment of the goal; assigns a rating to a goal; nominates a decision variable which is to be at the discretion of the decision maker(s); assigns limits to the range of states of a decision variable accessible to the decision maker(s); determines the laws which are to connect any interdependent properties, to connect the decision variables and context variables with the properties, and to connect any interdependent decision variables; and determines the state which a context variable is to take up. An arbiter may or may not at the same time be a decision maker.

14 A GOAL-DECISION SYSTEM
is a condition where a goal is governed by a property which in turn is governed by at least one decision variable, with or without an associated context variable. A goal-decision system contains one and only one property.

$O_n = fP_n = f(C_n, D_n)$ (where f signifies some relationship with, or function of, P_n or C_n and D_n).

In a given problem solving activity, the set of goals towards the attainment of which the activity is directed may give rise to a complex of goal-decision systems. Two goal-decision systems are said to be connected where their respective properties are interdependent and/or where their respective decision variables are in common or interdependent. Two or more connected goal-decision

11.11 (contd)

systems must be handled as a single complex system. Two unconnected goal-decision systems may be handled independently.

15 A SYSTEMATIC MODEL
of a goal-decision system or a complex of goal-decision systems is a logical model indicating the relationships of all the decision variables, context variables, and properties in the system(s). (see figs 11.2 and 11.3).

16 A HIERARCHICAL MODEL
of a complex of goal-decision systems is a logical model indicating which sets of goal-decision systems may be regarded as being groups, having a greater richness of interconnection between themselves than between the group and other goal-decision systems outside the group; which sets of groups may be regarded as being greater groups; and so on, in a hierarchy, until the whole complex is embraced. (see fig 11.4).

17 A PROGRAMME
for a complex of goal directed activities is a logical model indicating which activities are dependent for their commencement or completion, upon the completion of which other activities.

18 A PERFORMANCE SPECIFICATION
is the set of ordered pairs of goals and their associated ratings in a goal directed activity. Since the nomination of a goal is meaningless without reference to the property which governs it, and to the law connecting the goal with the property, a performance specification must nominate these, too.

$$\left\{\left((O_1 = fP_1), r_{o_1}\right), \left((O_2 = fP_2), r_{o_2}\right) \ldots\ldots\ldots \left((O_n = fP_n), r_{o_n}\right)\right\}$$

signifies a performance specification, with goals O_1, O_2 ....O_n

19 A PROPOSAL
is a set of states chosen by the decision maker(s) for the decision variable(s) in a problem solving activity and offered as a possible means for meeting the performance apecification.

$$\left\{D_1(i),\ D_2(i)\ \ldots.D_n(i)\right\}$$

signifies a proposal i for a set of decision variables D_1, D_2 ....D_n

20 A DESIGN
is <u>a proposal</u> in which <u>the decision variables</u> relate to the configuration of an artifact or an aggregation of artifacts.

21 THE PERFORMANCE
corresponding to a given <u>proposal</u> is the set of states of <u>properties</u> which are exhibited in the outcome, or which would be exhibited in the outcome if the proposal were to be implemented.

$\left\{P_1(x),\ P_2(x)\ \ldots\ldots\ P_n(x)\right\}$ signifies a performance x of a set of properties $P_1, P_2 \ldots . P_n$.

$\left\{P_1(x),\ P_2(x)\ \ldots\ldots\ P_n(x)\right\} = \left\{f\ D_1(i),\ D_2(i)\ \ldots\ldots\ D_n(i)\right\}$

where f signifies some function of proposal i.

22 THE MERIT
of <u>a performance</u> is the set of the degrees of attainment of the set of <u>goals</u> defined in <u>the performance specification</u>.

$\left\{O_1(y),\ O_2(y)\ \ldots\ldots\ O_n(y)\right\}$ signifies the merit y of a performance in respect of a set of goals $O_1,\ O_2 \ldots O_n$.

$\left\{O_1(y),\ O_2(y)\ \ldots\ldots\ O_n(y)\right\} = f\left\{P_1(x),\ P_2(x)\ \ldots\ldots\ P_n(x)\right\}$

where f is some function of performance x.

23 THE INDEX OF MERIT
of <u>a performance</u> is the ratio of the sum of the <u>rated</u> degrees of fulfilment of <u>the goals</u> to the sum of the <u>ratings</u>.

$$M_{iy}(t) = \frac{\left(r_{o_1}, O_1(y)\right) + \left(r_{o_2}, O_2(y)\right)\ \ldots\ldots\ \left(r_{o_n}, O_n(y)\right)}{r_{o_1} + r_{o_2}\ \ldots\ldots + r_{o_n}}$$

(when all the goals are fully attained, then $t = 1$. When some of the goals are partly attained, then $t < 1$. Larger values of t indicate greater merit than smaller values of t. When t or any one value of y is less than .5, then the performance is not acceptable.)

where

M	signifies an index of merit.
M_{iy}	signifies the index M for the performance y relating to a proposal i.
$M_{iy}(t)$	signifies a particular value t of index M_{iy} (where t is some number between zero and unity).
$M_{iy_2}(t_2)$	signifies a particular value t_2 of index M_{iy} where the state x of the index of expediency P_{E_i} is also taken into account.

24 THE EXPEDIENCY
of a proposal is the value to the participants of proceeding with the implement tion of it, in view of the relations which may exist between the marginal cost of servicing the capital to be employed, the return it can be expected to produce (if successful), and the probability of success. Expediency may thus be a property in the problem. An index of expediency is given by:

$$P_{E_i} = \frac{Ri}{Fi} - \frac{1}{\theta\{P_n(x)\}}$$

where

P_E	signifies the property 'expediency'
P_{E_i}	signifies the expediency of proceeding with proposal i
R_i	signifies the expected return per cent on capital employed by proposal i
F_i	signifies the marginal cost per cent of servicing the capital employed
θ	signifies probability
$\theta\{P_n(x)\}$	signifies the probability that performance x of the set of properties $P_1, P_2 \ldots\ldots P_n$ will, in the event, be achieved

A negative index of expediency suggests that, on financial grounds at least, the proposal should not be proceeded with. The expected return R_i might reflect the merit of the proposal in other respects.

$R_i = fM_{iy}(t)$

The overall merit of the proposal, including its performance in respect of expediency is given by:

$$M_{iy_2}(t_2) = \frac{\sum\left(r_{o_n} \cdot O_n(y)\right) + \left(r_{P_{E_i}} \cdot P_{E_i}(x)\right)}{\sum r_{o_n} + r_{P_{E_i}}}$$

where

$M_{iy_2}(t_2)$ signifies the state t_2 of the index of merit M associated with performance y_2 of proposal i, taking into account its expediency P_{E_i}.

$r_{P_{E_i}}$ signifies the weighting to be given to financial expediency in calculating overall expediency.

25 AN EXPEDIENCY MATRIX
is a display of the indices of expediency or indices of merit including expediency associated with various alternative proposals and various possible outcomes. Amongst the alternative proposals considered might be the proposal to abandon the project. The possible outcomes tabulated might be those associated with selected points in the distribution of the ranges of states of those properties which are the outputs of probabilistic systems (fig 11.5).

26 PROBLEM SOLVING PROCEDURE
in a problem solving activity consists in action calculated to complete the following phases:

1 Given the performance specification relating to the activity;
2 Given a set of ranges of the set of decision variables at the discretion of the decision maker(s);
3 Identify the laws connecting any interdependent properties nominated by the performance specification;
4 Identify the complex of goal-decision systems connecting the decision variables and any context variables with the properties, together with the laws governing the systems;
5 Identify the laws connecting any interdependent decision variables;
6 Establish the prevailing states of the context variables;
7 Postulate one or more proposals for a set of compatible states of the decision variables;

8 Determine the performance which would arise from the implementation of each of the proposals;
9 Determine the merits of each performance;
10 Calculate the index of merit relating to each performance, NOT taking into account its performance in respect of expediency.
11 Determine the expediency of proceeding with each proposal.
12 Calculate the index of merit relating to each performance, INCLUDING its performance in respect of expediency, and select the best proposal.

These phases may be represented symbolically thus:

1 Given requirements
$$\left\{\left((O_1=fP_1),r_{o_1}\right),\ \left((O_2=fP_2),r_{o_2}\right)\ \ldots\ \left((O_n=fP_n),r_{o_n}\right)\right\}$$

2 Given resources
$$\left\{\left(D_1(g),D_1(h)\right),\left(D_2(g),D_2(h)\right)\ \ldots\ \left((D_n(g),D(h)\right)\right\}$$

3 Identify performance laws
$$\left\{(P_1=fP_2),(P_3=fP_4)\ \ldots\ (P_{(n-1)}=fP_n)\right\}$$

4 Identify systems laws
$$\left\{\left(P_1=f(C_1,D_1)\right),\ \left(P_2=f(C_2,D_2)\right)\ \ldots\ \left((P_n=f(C_n,D_n)\right)\right\}$$

5 Identify resource laws
$$\left\{(D_1=fD_2),(D_3=fD_4)\ \ldots\ (D_{(n-1)}=fD_n)\right\}$$

6 Establish context
$$\left\{C_1(k),C_2(k)\ \ldots\ C_n(k)\right\}$$

7 Postulate designs
$$\left\{D_1(i),D_2(i)\ \ldots\ D_n(i)\right\} \text{ and } \left\{D_1(j),D_2(j)\ \ldots\ D_n(j)\right\}$$

8 Determine performances
$$\left\{P_1(x),P_2(x)\ \ldots\ P_n(x)\right\} \text{ and } \left\{P_1(w),P_2(w)\ \ldots\ P_n(w)\right\}$$

9 Determine merits
$$\left\{O_1(y),O_2(y)\ \ldots\ O_n(y)\right\} \text{ and } \left\{O_1(z),O_2(z)\ \ldots\ O_n(z)\right\}$$

10 Calculate rated-objective merit-indices, omitting reference to expediency
$$M_{iy}(t) = \frac{\sum(r_{o_n}\cdot O_n(y)}{\sum r_{o_n}} \quad \text{and} \quad M_{jw}(t) = \frac{\sum(r_{o_n}\cdot O_n(w)}{\sum r_{o_n}}$$

11 Establish expediencies

$$P_{E_i}(x) = \frac{R_i}{F_i} - \frac{1}{\theta}\{P_n(x)\} \quad \text{and} \quad P_{E_j}(w) = \frac{R_j}{F_j} - \frac{1}{\theta}\{P_n(x)\}$$

12 Calculate rated-objective merit-indices, including reference to expediency

$$M_{iy_2}(t_2) = \frac{\sum\left(r_{o_n} \cdot O_n(y)\right) + \left(r_{P_{E_i}} \cdot P_{E_i}(x)\right)}{\sum r_{o_n} + r_{P_{E_i}}}$$

$$\text{and} \quad M_{jw_2}(t_2) = \frac{\sum\left(r_{o_n} \cdot O_n(w)\right) + \left(r_{P_{E_j}} \cdot P_{E_j}(w)\right)}{\sum r_{o_n} + r_{P_{E_i}}}$$

27 REITERATIVE ROUTINE

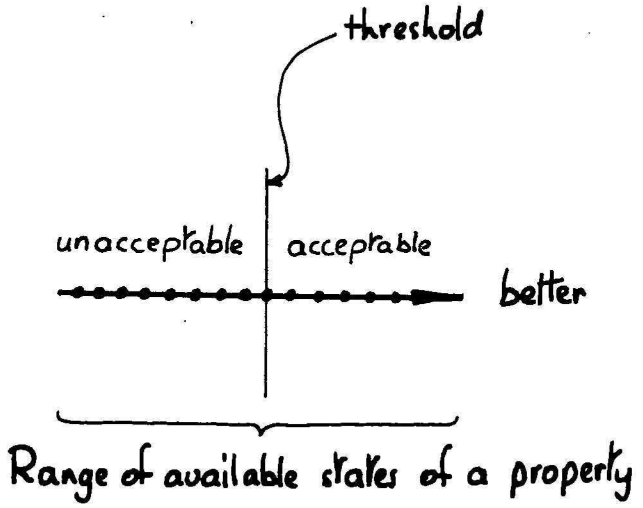
In practice, it is seldom possible to complete each phase in sequence. The performance specification for example, is often in a state of continuous development and amendment, almost to the end of the problem solving activity. Problem solving procedure therefore frequently consists in the following routine, reiterated for one goal-decision system after another as information becomes available and the overall picture clarifies (see fig 11.6):

		Ref. column no. in fig 11.3
1	appraise overall problem in the light of the programme, systematic model, hierarchical model, partial solutions and merit indices, as developed so far	
2	select the next most dominant subproblem	
3	identify the arbiters entitled to nominate objectives in this subproblem	
4	in consultation with the arbiters, identify the objectives in the subproblem	col 1
5	identify the property defined by each objective	col 2
6	by agreement between the arbiters, assign importance ratings to the objectives	col 3
7	in consultation with the arbiters, determine the limiting states of the properties which are to be equivalent to the ideal and threshold degrees of fulfilment of their respective objectives	cols 4 and 5
8	establish the relationships (internal or specific laws) connecting varying states of the properties with varying degrees of fulfilment of their respective objectives	col 6

9	establish the domain of acceptability defined by the superimposition of the limiting states of the properties (if necessary, in order to gain a positive domain of acceptability, negotiate changes at 7, and repeat)	cols 4 and 5
10	identify the relationships (external or general laws) governing any interdependence existing between the states of properties identified at 5 above	cols 4 and 5
11	establish the realm of feasibility defined by the compatible ranges of states of the properties (if necessary, in order to obtain a positive realm of feasibility, take an inventive step creating new relationships at 10, and repeat)	cols 4 and 5
12	establish the arena within which a performance must be found, as defined by the superimposition of the domain of acceptability and the realm of feasibility (if necessary, in order to obtain a positive arena for performance, negotiate changes at 7, and/or create new relationships at 10, and repeat)	cols 4 and 5
13	identify the context variables which contribute to governing the goal-decision systems under examination (including those context variables which arise from subproblems already handled)	col 17
14	identify the decision variables governing the states of the properties	col 8
15	erect a (or improve the existing) systematic model and hierarchical model of the goal-decision systems connecting the decision variables with the properties, and the properties with the objectives, in the subproblem	
16	identify the laws connecting the varying states of the decision variables and context variables (inputs) with the varying states of the properties (outputs) in the goal-decision systems identified at 15	col 9
17	establish the ranges of states of the individual context variables which apply to the case in hand	col 10
18	establish the context defined by the superimposition of the prevailing states of the context variables	col 10
19	establish the ranges of states available in the individual decision variables	cols 11 and 12
20	identify the laws governing any interdependence existing between the states of the decision variables at 14	cols 11 and 12
21	establish the scope of the design resource defined by the compatible ranges of states of the decision variables (if necessary, in order to obtain a positive scope of design resources, negotiate changes at 19, and repeat)	cols 11 and 12

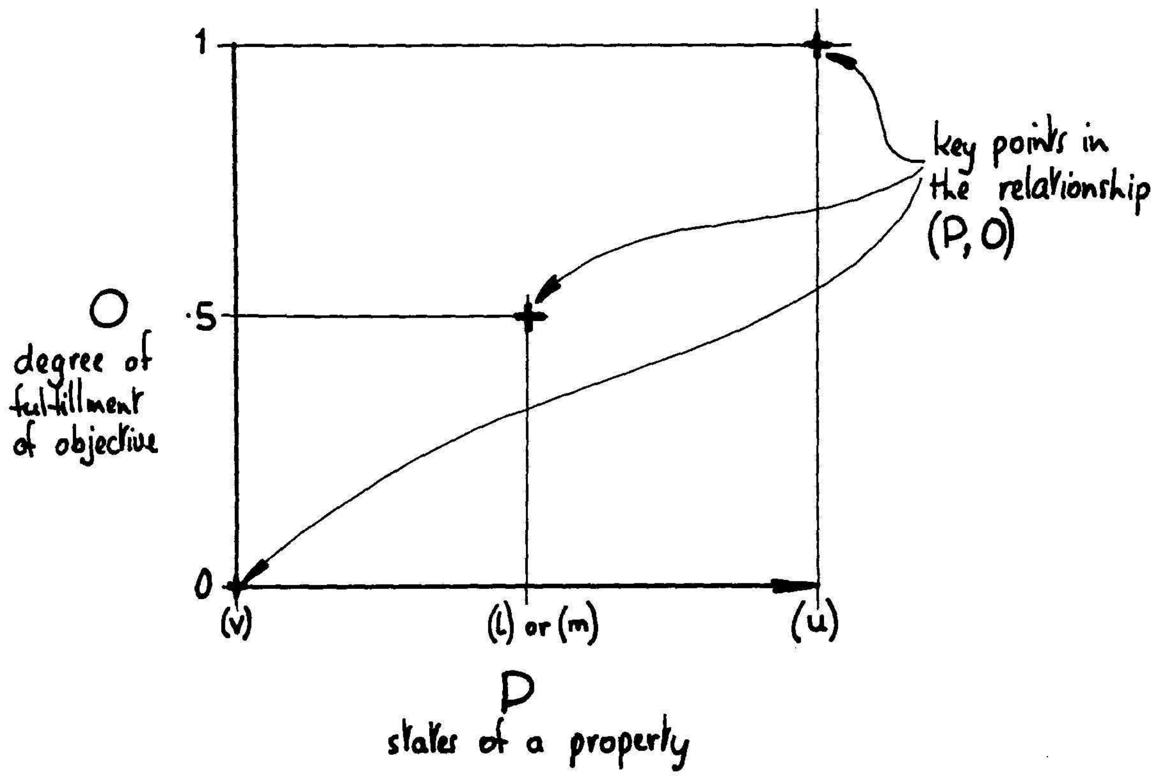
22	erect one or more analogues to represent the laws identified at 10, 16 and 20	
23	identify the decision maker(s) entitled to select states of the decision variables in the subproblem	
24	by agreement amongst the decision makers, and using the analogues erected at 22 for the laws at 20, select a self-compatible set (design i) of states for the decision variables	col 13
25	using the analogues erected at 22 for the laws at 16, determine the resultant set (performance x) of states of the properties	col 14
26	establish whether or not performance x lies within the arena for performance defined at 12 (if not repeat from 24). If no solution is obtainable, create new relationships between the properties at 10 (inventive step), or re-work subproblems giving rise to context variables at 13 (re-appraisal), or negotiate new limiting values for the properties at 7 (re-statement), and repeat	cols 4 and 5
27	evaluate index t of merit y of overall performance x arising from proposal i in respect of all objectives handled so far (rated-objective merit-index $M_{iy}(t)$)	cols 16 to 20
28	evaluate expediency $P_E(x)$ of proceeding with proposal i	cols 20 to 24
29	re-evaluate index t_2 of merit y_2 of overall performance x_2 arising from proposal i in respect of all objectives handled so far (re-mi $M_{iy_2}(t_2)$)	cols 25 to 27
30	repeat from 24 (alternative design j) as often as necessary, or as often as time and money will permit, until the index t_2 of merit z_2 of overall performance w_2 is as high as possible (rated-objective merit-index $M_{jz2}(t_2)$)	
31	identify and validate any critical assumptions or approximations made during the course of the solution of the subproblem	
32	repeat from 1 until the overall problem is resolved	

11.12 The argument and definitions developed in this thesis are offered as a conceptual framework within which further case studies and more detailed tabulations might be accumulated.



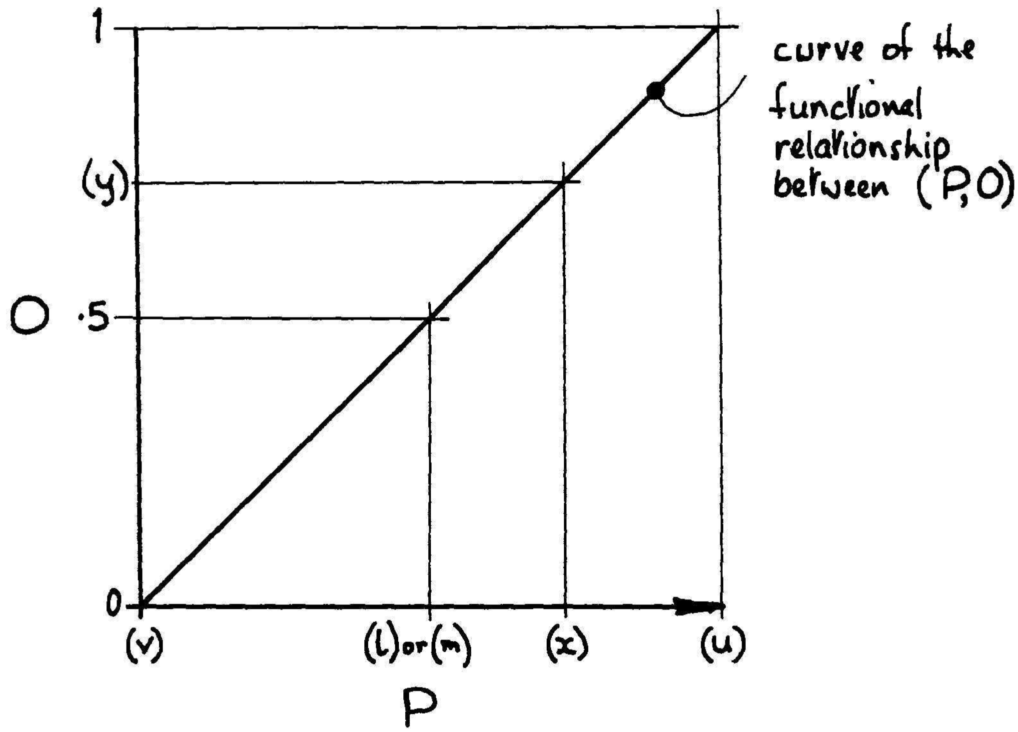
An objective nominates a property, indicates the direction in which changes would be for the better, and identifies a threshold between acceptable and unacceptable states.

fig 2.1



The degree of fulfillment of objective is a dependent variable, governed by the state of its associated property

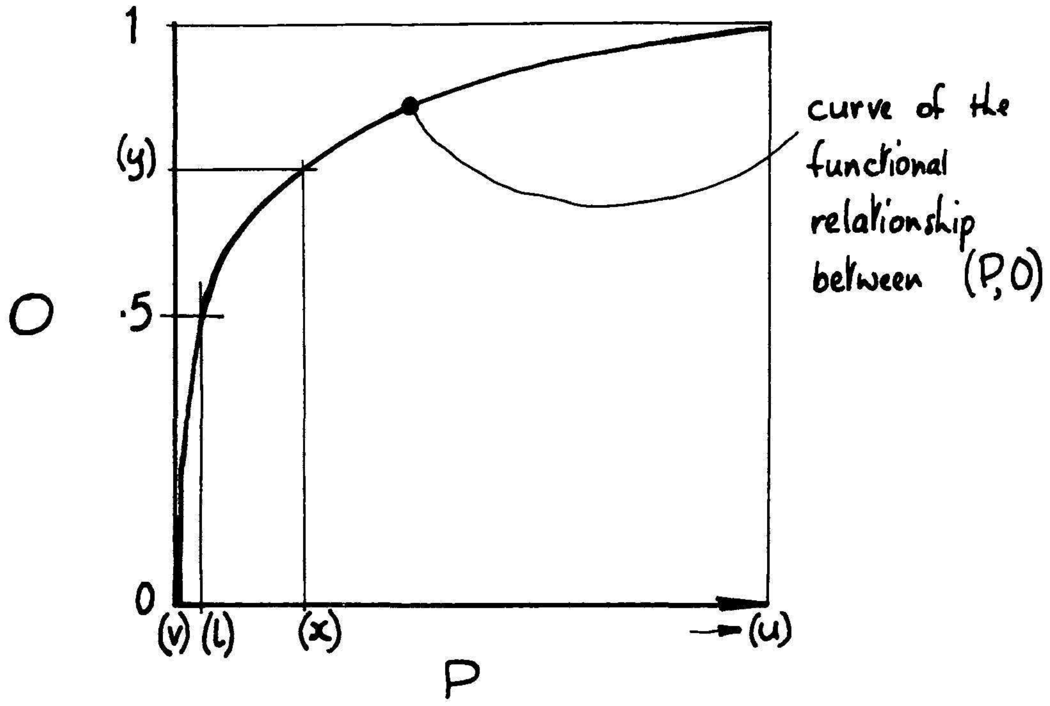
fig 2.2



Example of a relationship between an objective and a property taking the form:

$$O(y) = 1 + \frac{P(x) - P(u)}{2\left(P(u) - P(l)\right)}$$

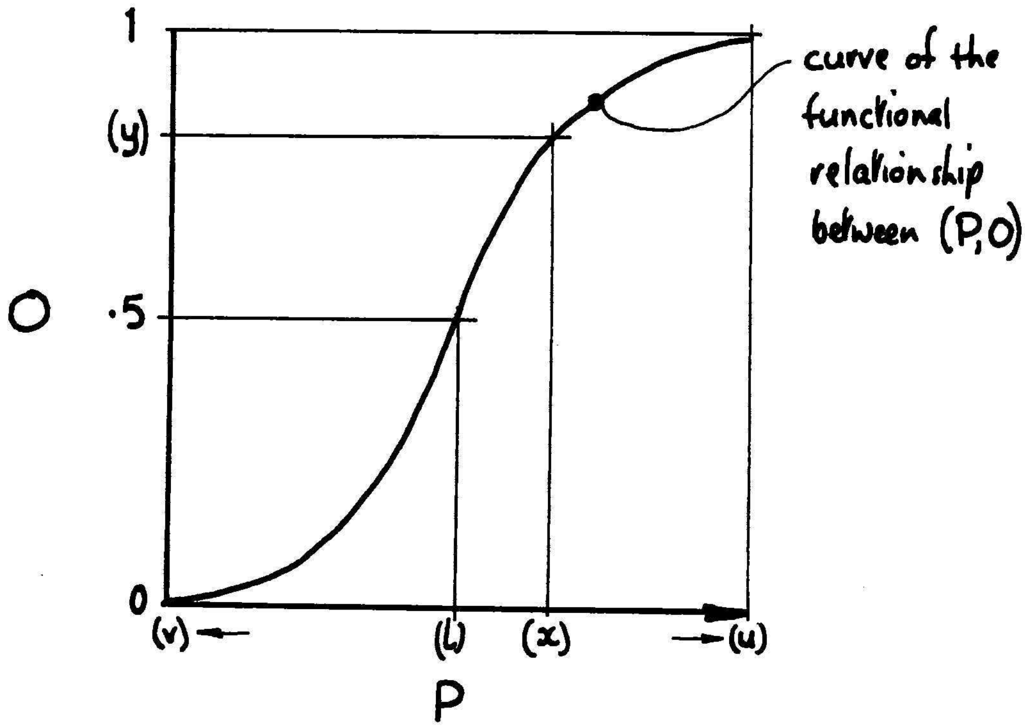
fig 2.3



Example of a relationship between an objective and a property taking the form:

$$O(y) = 1 - \frac{P(l)}{2P(x)}$$

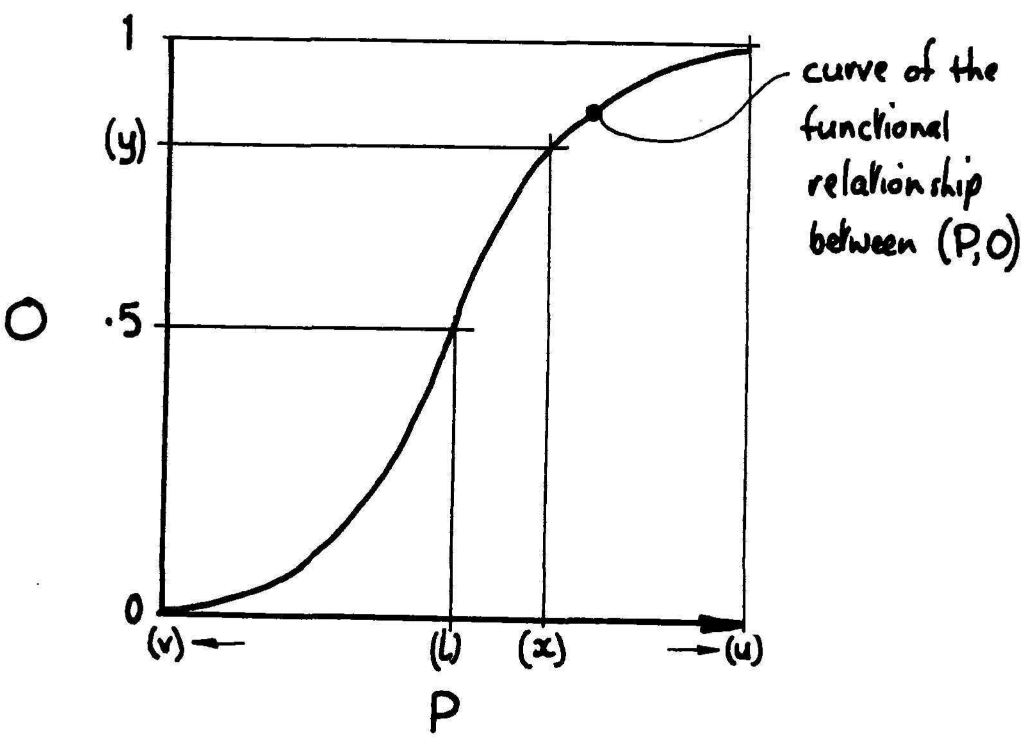
fig 2.4



Example of a relationship between an objective and a property taking the form:

$$O(y) = \frac{1}{2} + \frac{\arctan\left(P(x) - P(l)\right)}{180}$$

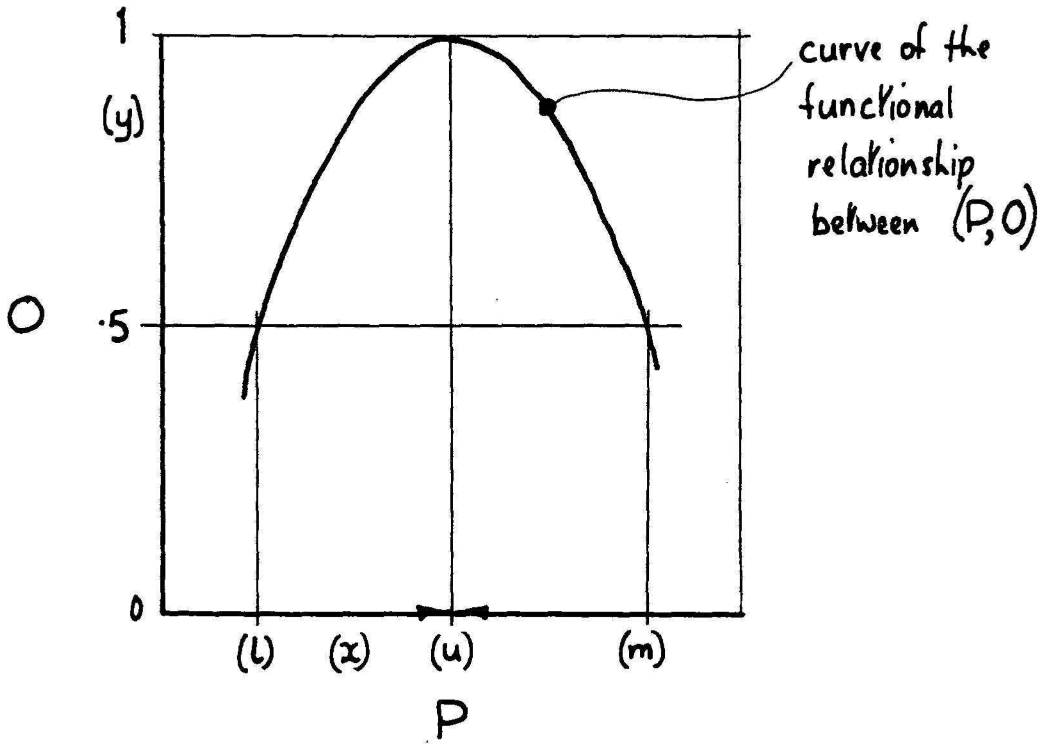
fig 2.5



Example of a relationship between an objective and a property taking the form:

$$O(y) = \frac{1}{2} + \frac{\arctan\left(P(x) - P(l)\right)}{180}$$

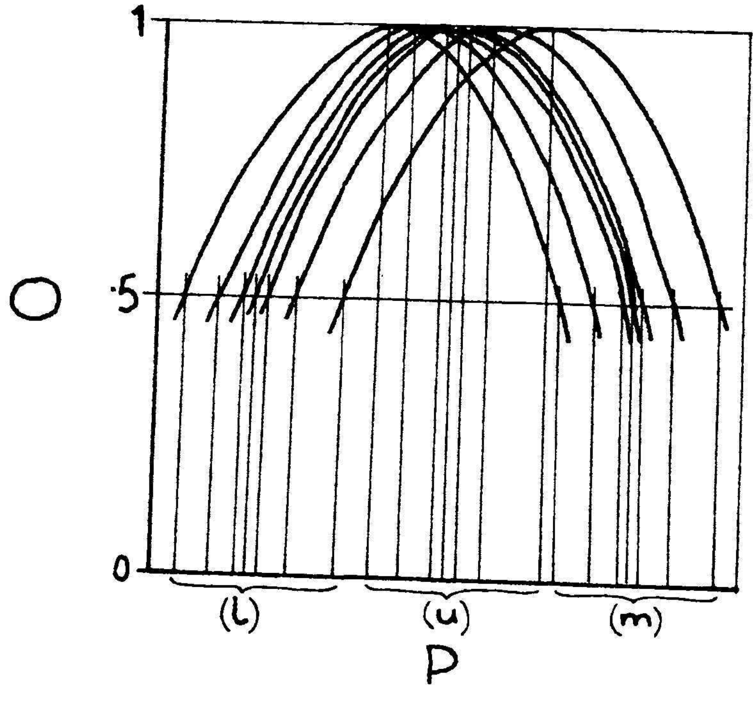
fig 2.5



Example of a relationship between an objective and a property taking the form:

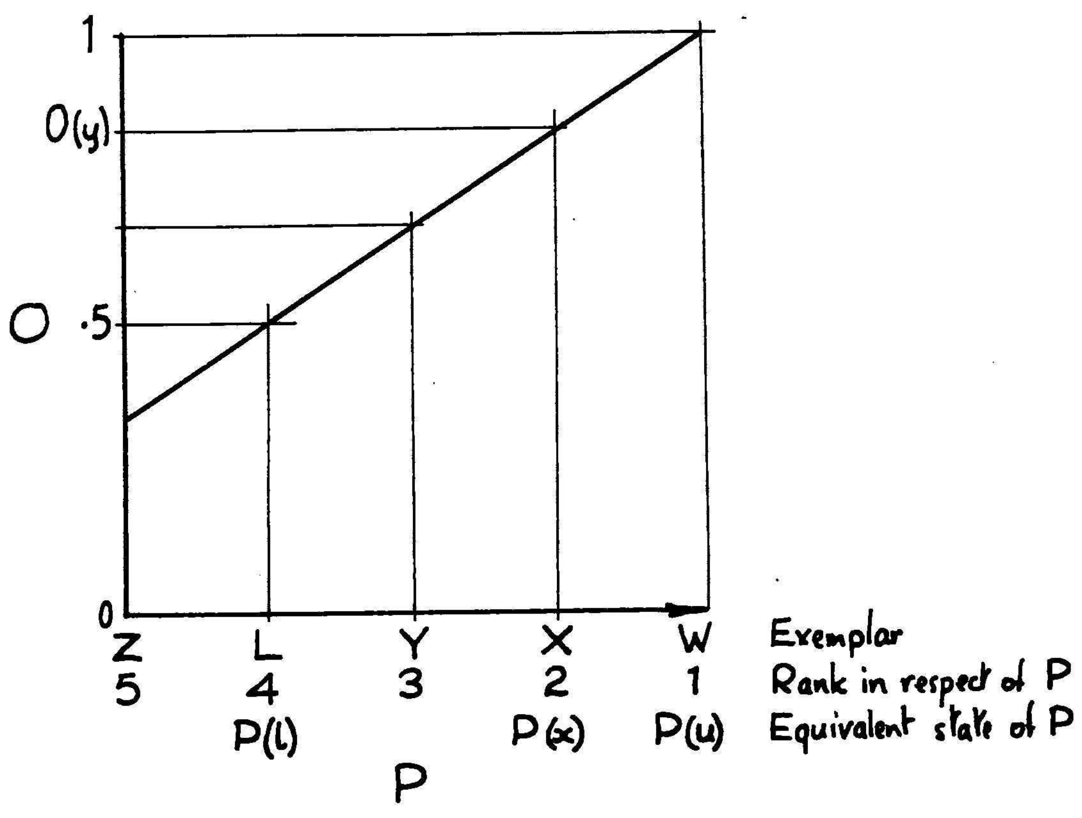
$$O(y) = 1 - \frac{\left(P(x) - P(u)\right)^2}{2\left(P(u) - P(l)\right)^2}$$

<u>fig 2.6</u>



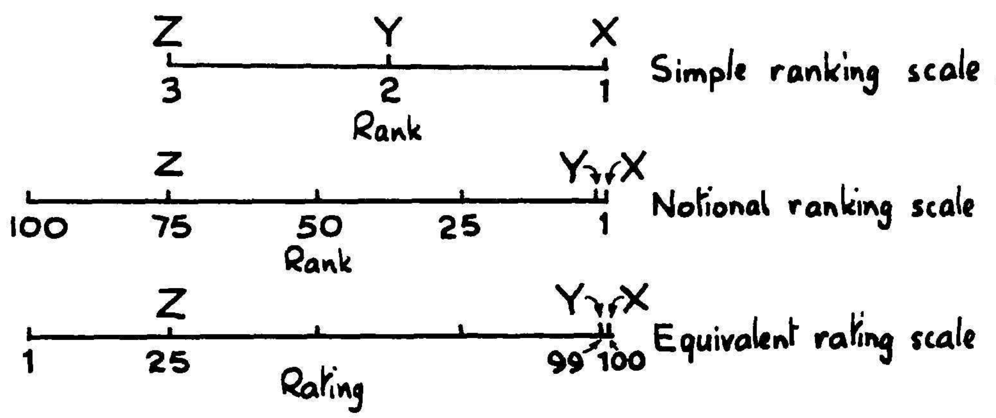
Example of a property with statistically distributed optimum and limiting values

fig 2.7



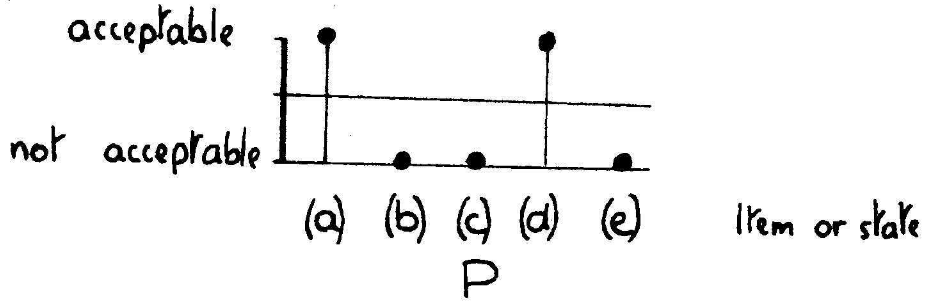
Properties whose states cannot be expressed in terms of interval scales may be expressed in terms of exemplars on an ordinal scale

fig 2.8



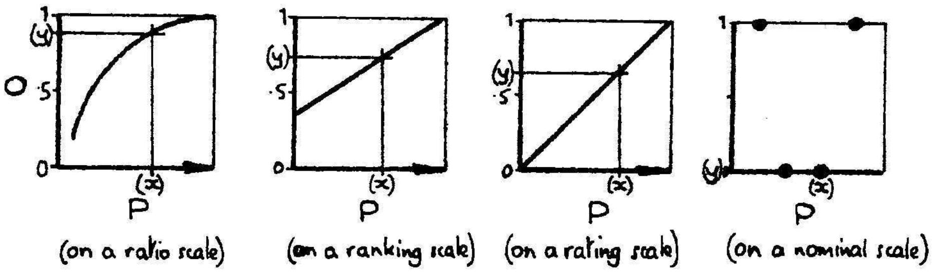
Where, in the real-world situation, the steps between rankings are felt to be unequal, the items may be ranked as if they were in a much larger collection. This may be conceived as a rating scale, where each item is assigned 'merit points' or 'an importance rating'.

fig 2.9



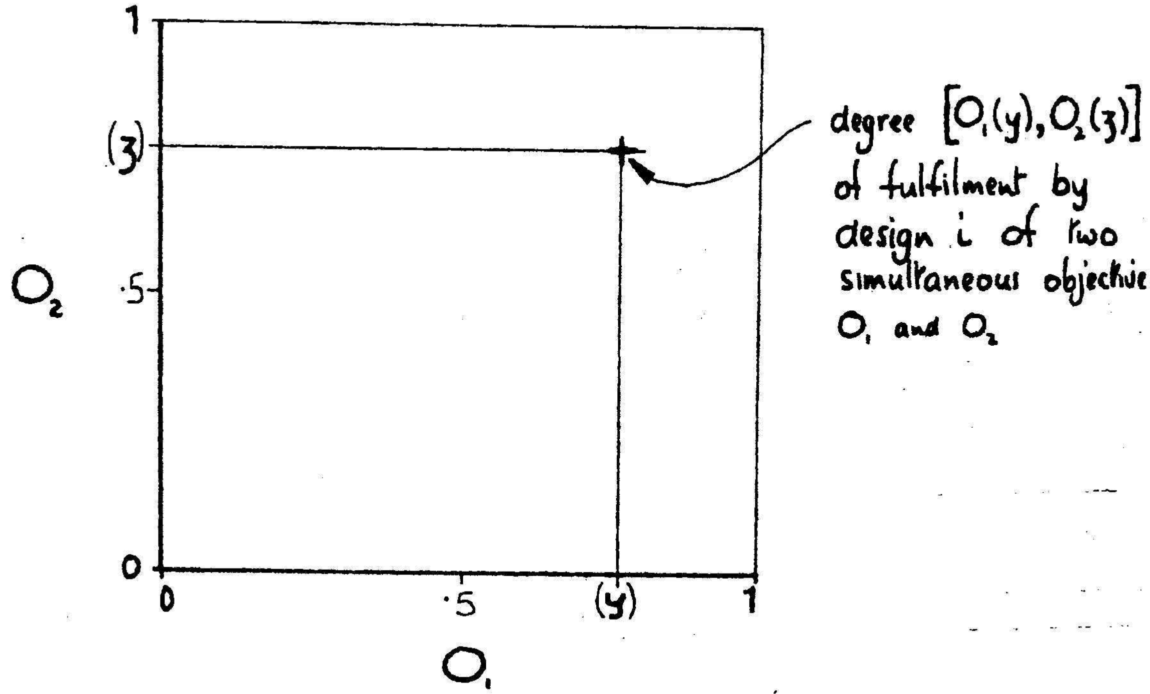
There are some properties whose various states cannot be set out on either ratio scales or ordinal scales, but merely identified. The objective may still nominate one or more states as 'acceptable' and others as 'unacceptable'.

fig 2.10



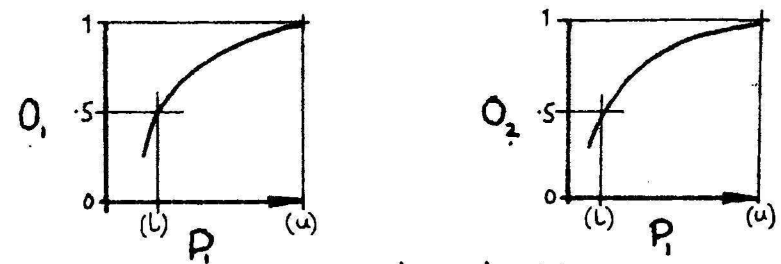
The alternative states of all the types of properties may be assigned relationships with degrees of fulfilment of objective, and any particular state of the property will be associated with a value for O(y) lying between zero and unity

fig 2.11

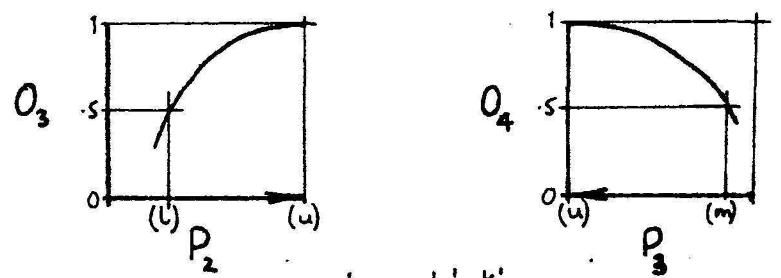


A given design may fulfil two simultaneous objectives to the same or differing degrees

fig 2.12



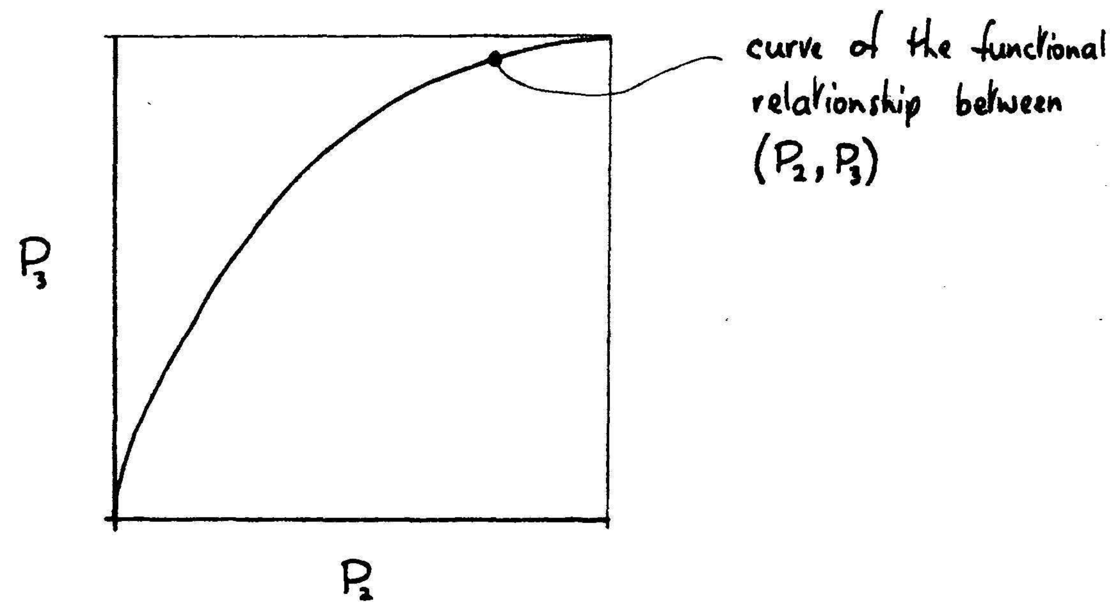
co-operating objectives



opposing objectives

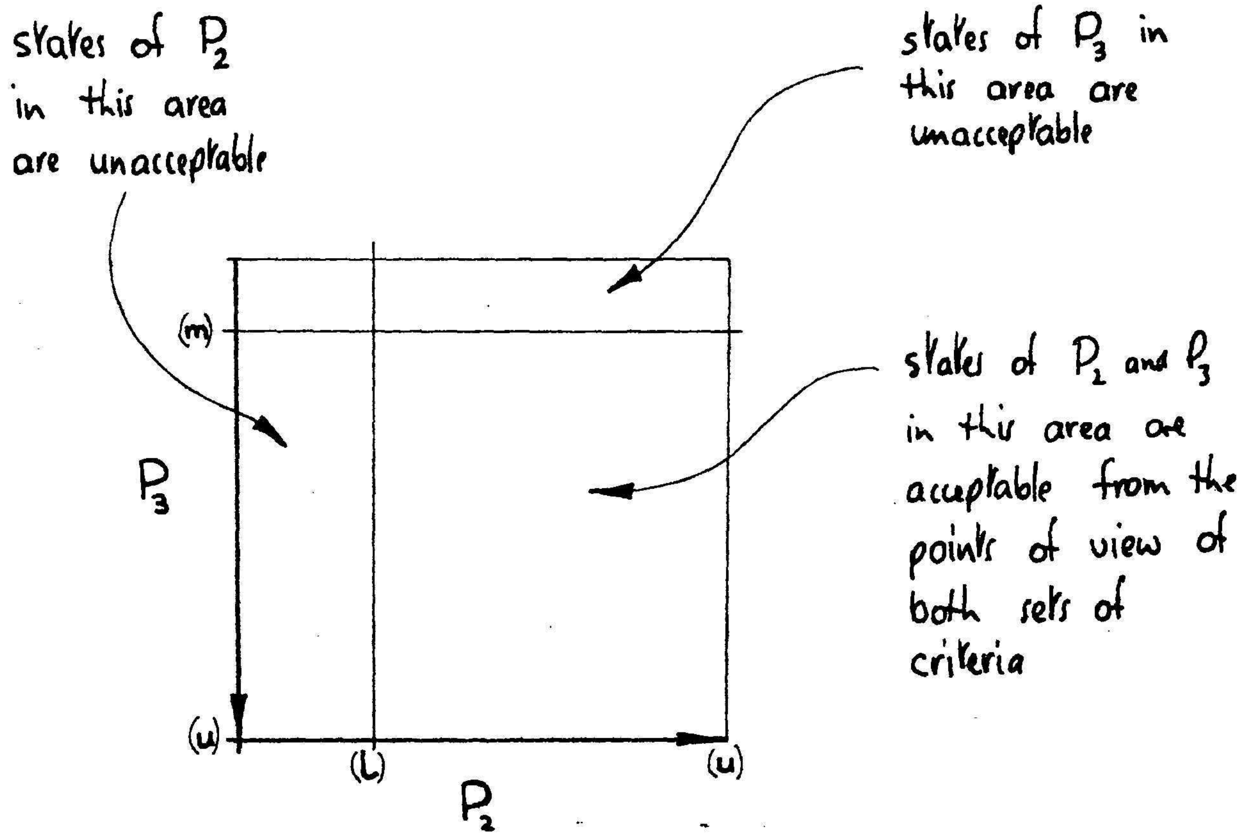
Two objectives referring to the same (or interdependent) properties and pointing to the same ideal states may be referred to as co-operating objectives. Two objectives referring to the same (or interdependent) properties and pointing to opposite ideal states may be described as opposing objectives.

fig 2.14



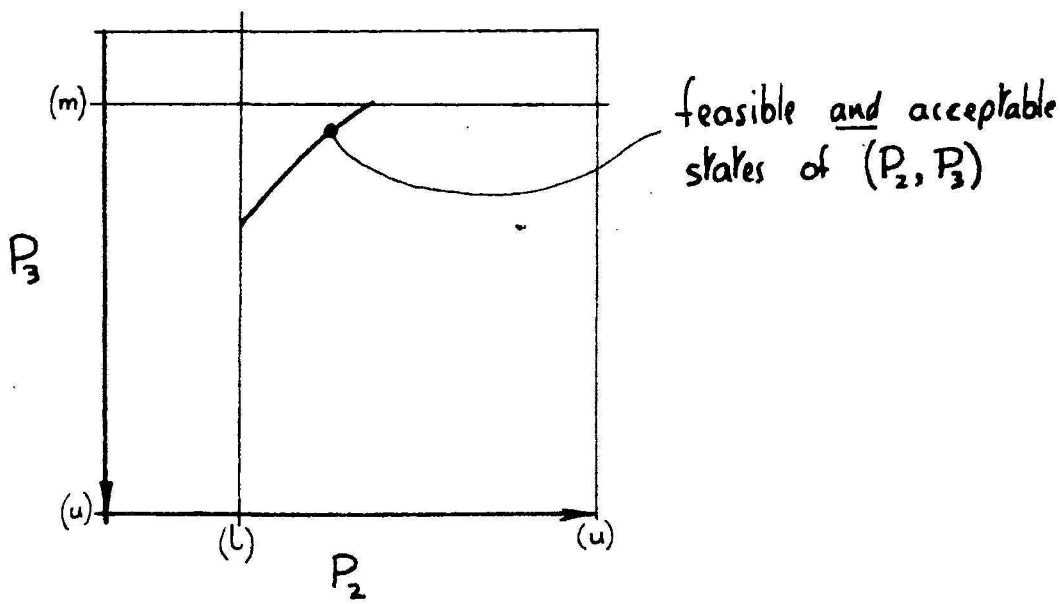
Where two properties are interdependent the locus of the points of coincidental states of the properties marks out a curve of feasible mutual states

fig 2.15



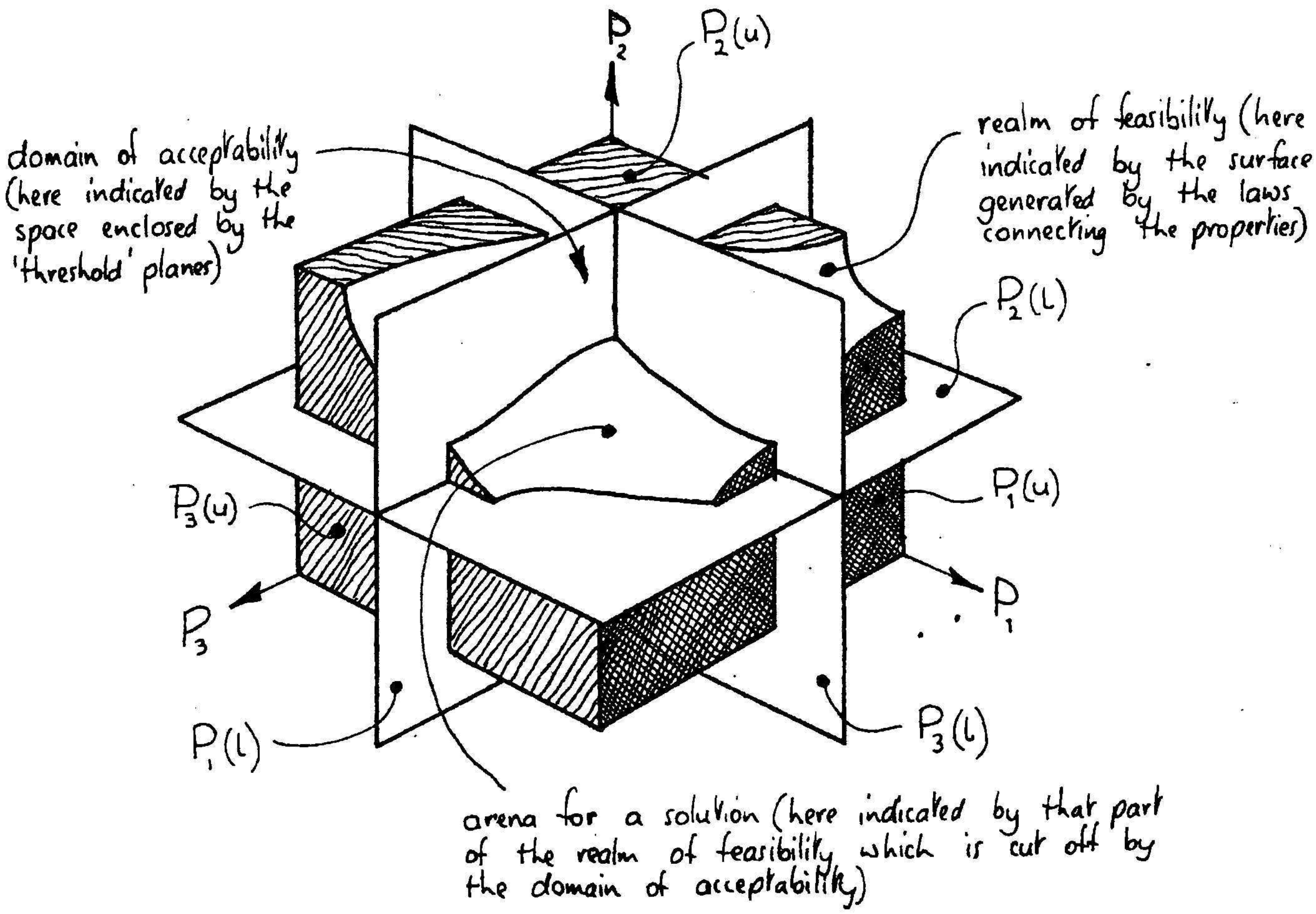
The spaces marked off by the limiting states of the properties indicate the field of mutually acceptable states

fig 2.16



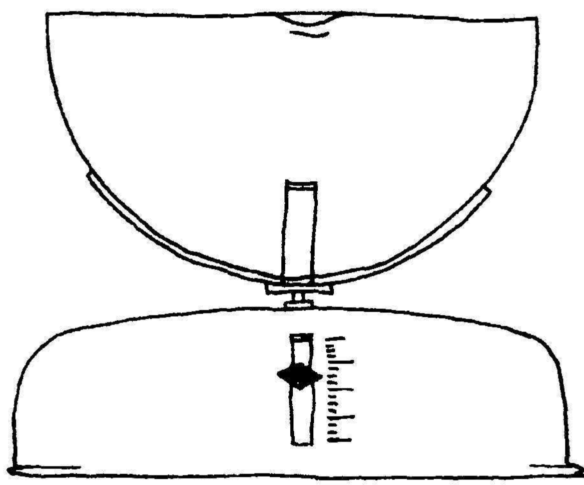
The superimposition of the fields of acceptable states of a property upon curves of feasible states marks out the range of feasible and acceptable states

fig 2.17



The interdependence of the states of the properties constitutes an n-dimensional hypersurface or realm of feasibility. The product of the erection of limiting states of the properties is an n-dimensional space or domain of acceptability. The superimposition of the domain of acceptability on the realm of feasibility marks out the arena within which a solution is to be selected.

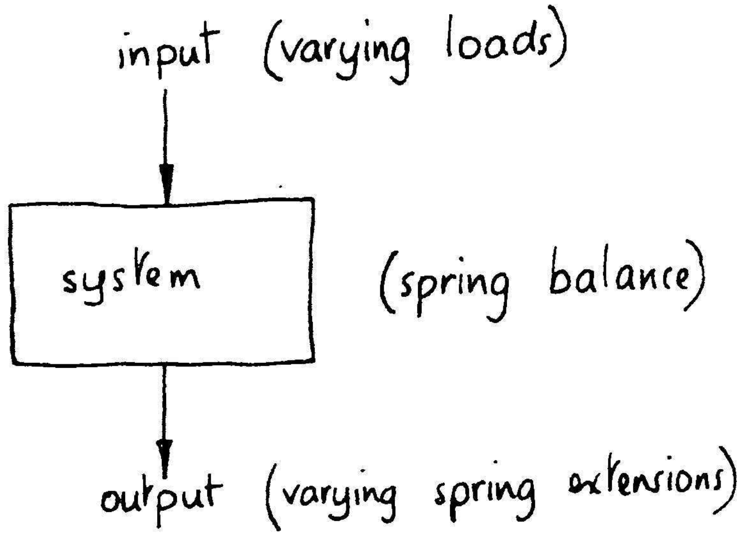
fig 2.18



?

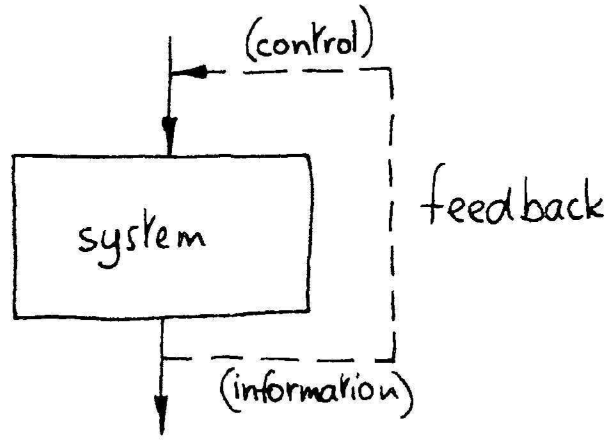
A spring balance is a system where the addition of a load causes a spring to extend or compress

fig 3.1



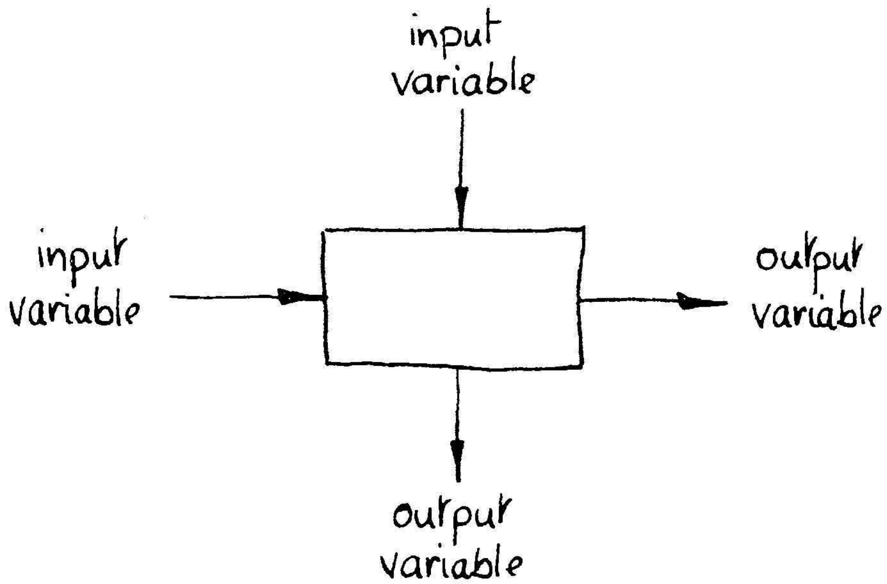
Spring balance described in systems terms

fig 3.2



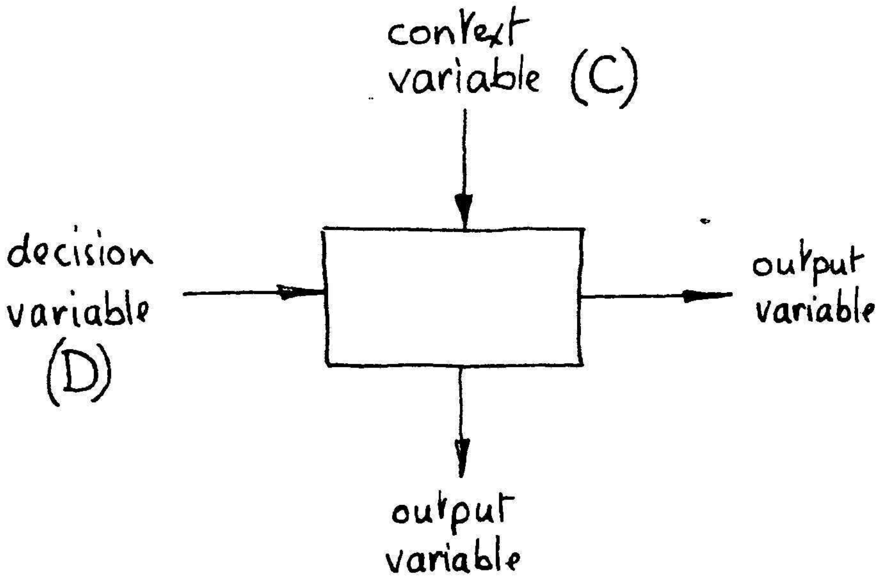
The feedback concept in systems theory

fig 3.3



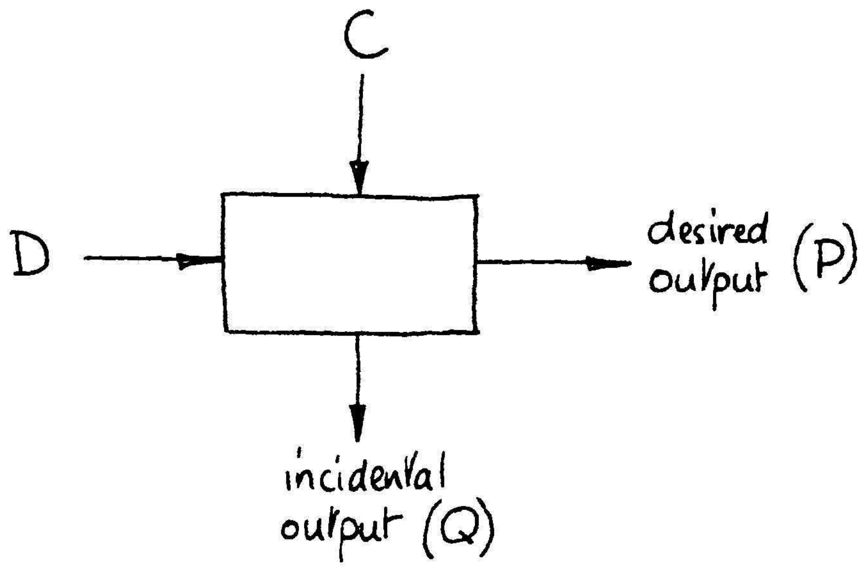
Systems may have more than one input and more than one output

fig 3.4



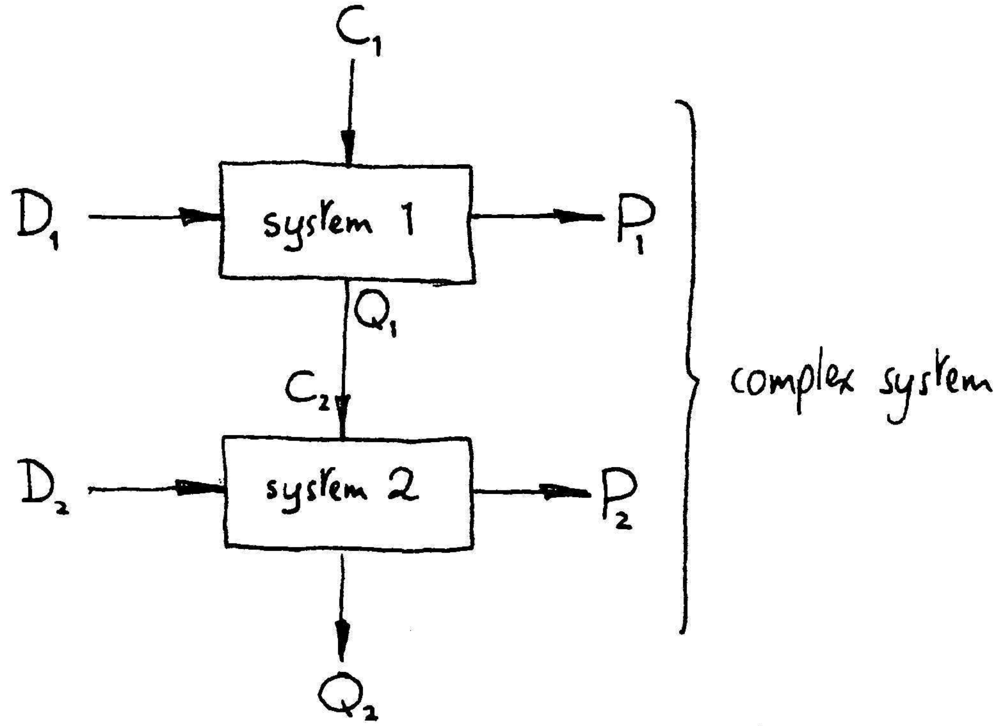
Some variables (C) may be outside the control of the decision maker and some variables (D) may be within his control

fig 3.5



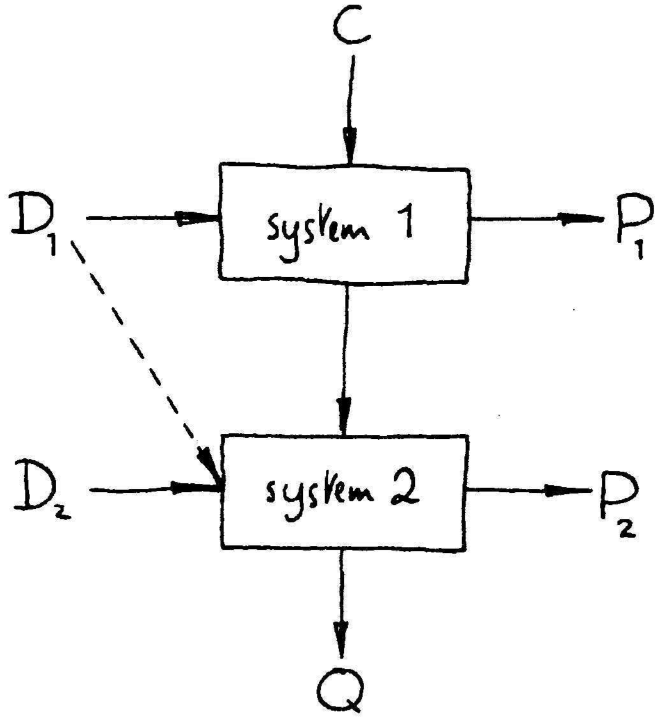
Some output variables (P) will be those which the decision maker wishes to control and others (Q) may be merely incidental

fig 3.6



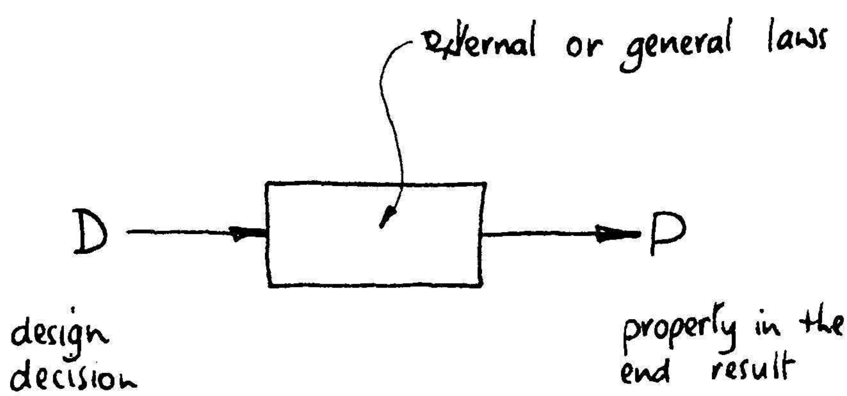
An incidental output from one system may be a context variable in another

fig. 3.7



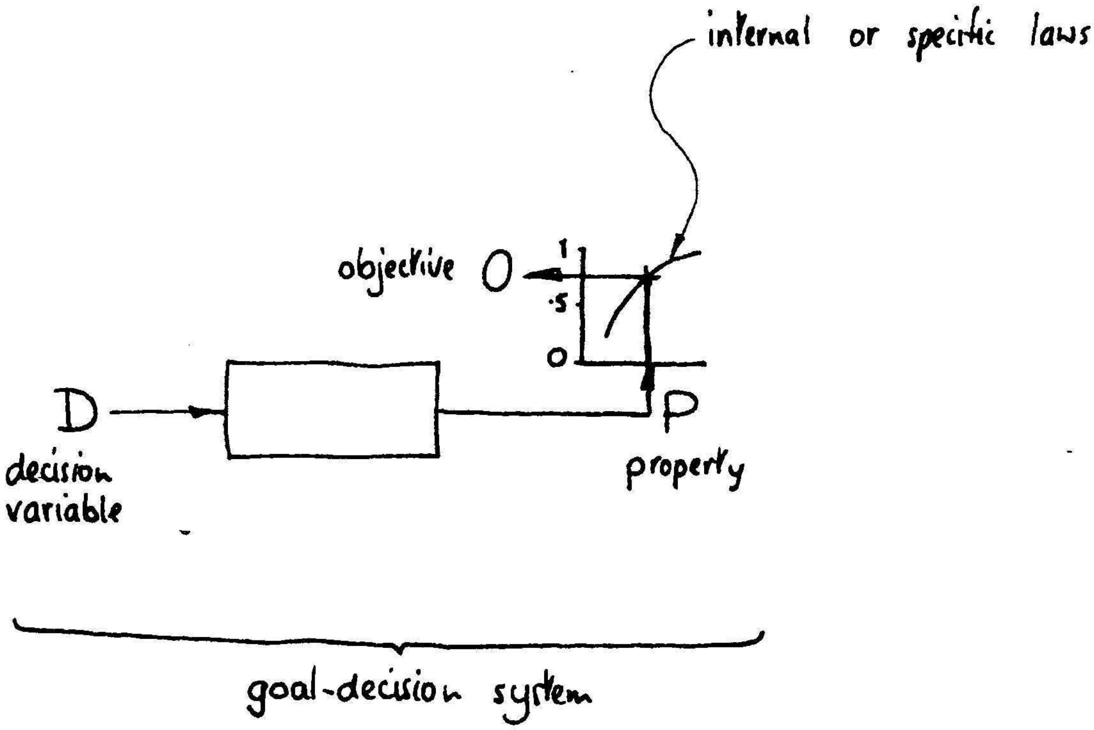
A decision variable in a system which partly controls another system may be regarded as being a decision variable in the second system also

fig 3.8



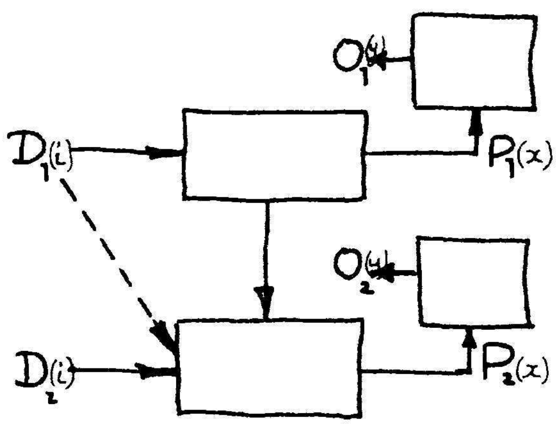
A design problem may be expressed in systems terms

fig 3.9



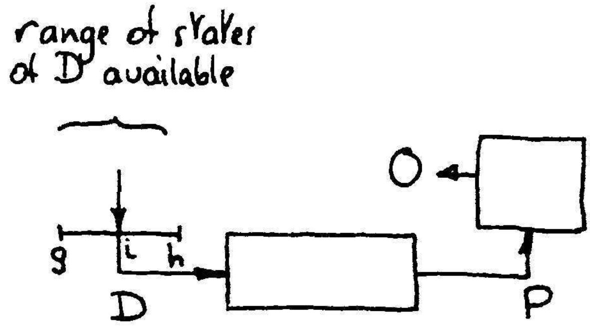
Where a decision variable controls a property and the property controls a degree of fulfilment of objective, the whole is said to form a goal-decision system

fig 3.10



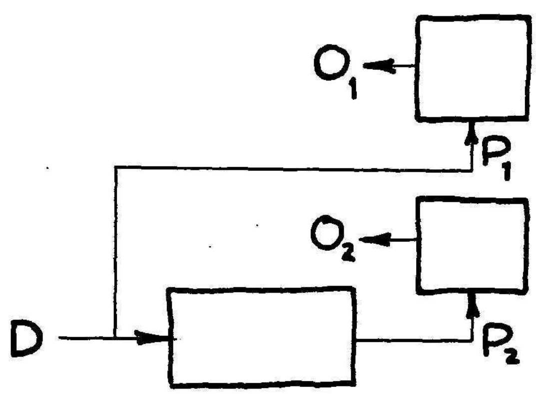
The aim is to select a set of states for the decision variables, such that the degree of fulfilment of objectives is optimised

fig 3.11



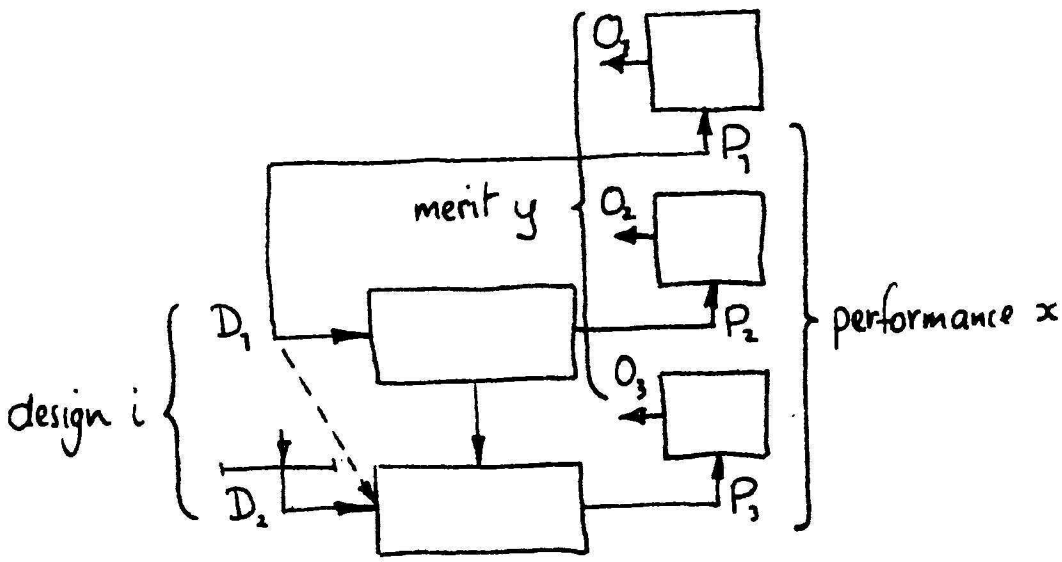
The decision variables may be subject to limitations

fig 3.12



A decision variable, as well as controlling a property, may itself be a property, having more meritorious and less meritorious states in themselves

fig 3.13

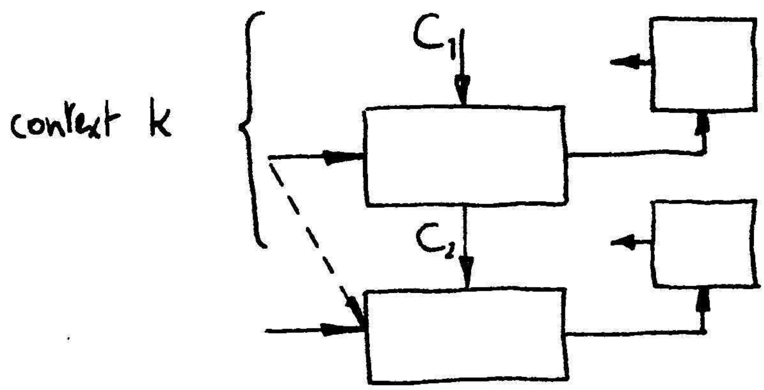


A set of states i for the ~~design~~ decision variables constitutes a design

A set of states x for the properties constitutes a performance

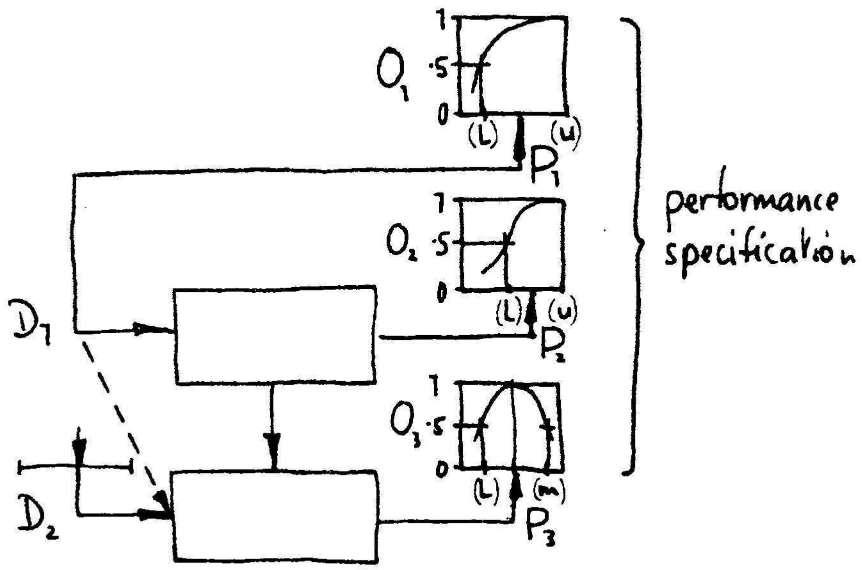
A set of states y for the degrees of fulfilment of objectives constitutes the merit of a performance

fig 3.14



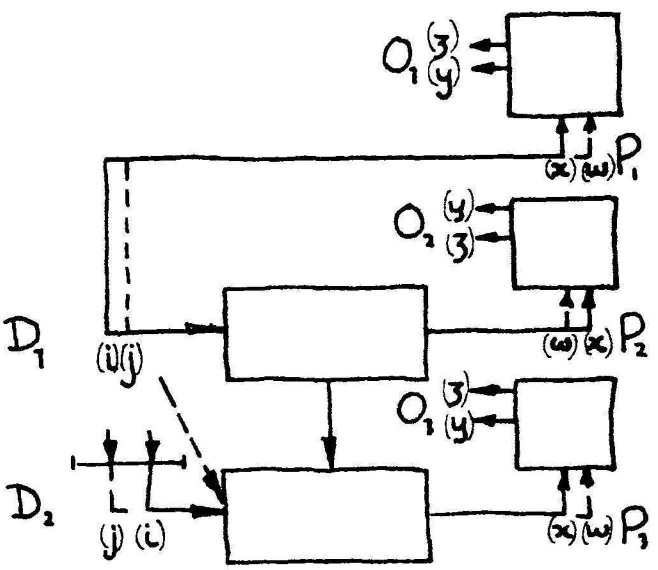
A set of states k for the context variables constitutes the context

fig 3.15



A performance specification lists the properties required and defines the relationships between states of the properties and degrees of fulfilment of objective

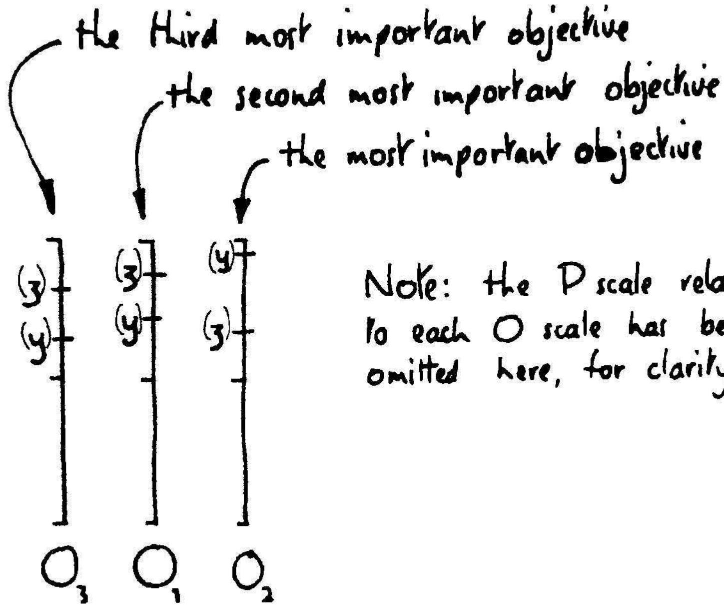
fig 3.16



Design i might give rise to performance x of merit y

Design j might give rise to performance w of merit z

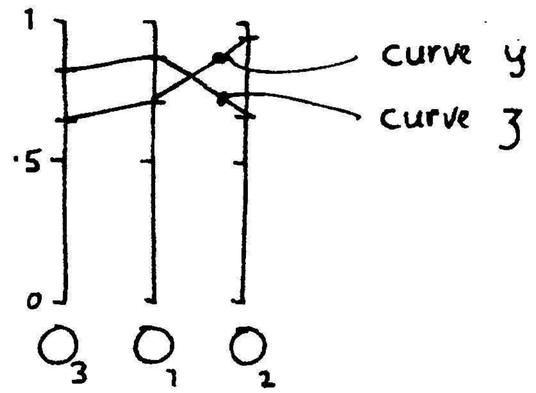
fig 3.17



Note: the P scale relating to each O scale has been omitted here, for clarity

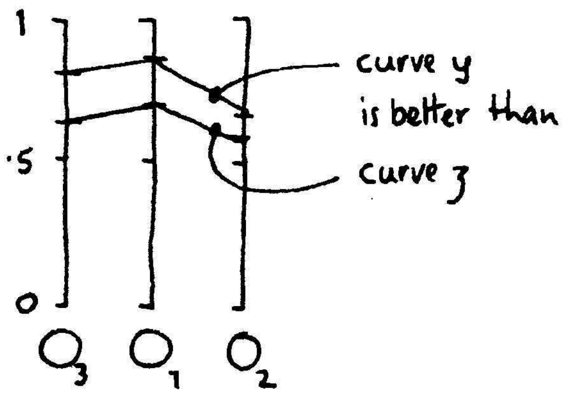
To assist in discerning relative overall merits the objective fulfilment scales may be represented arranged in order of importance

fig 3.18



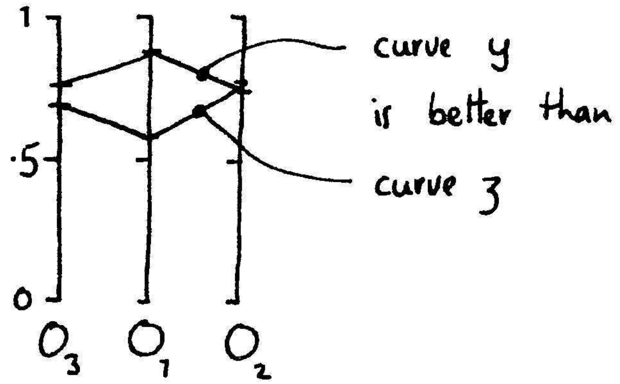
Comparison is simplified if the points representing the degrees of fulfilment of objective relating to each performance are joined

fig 3.19



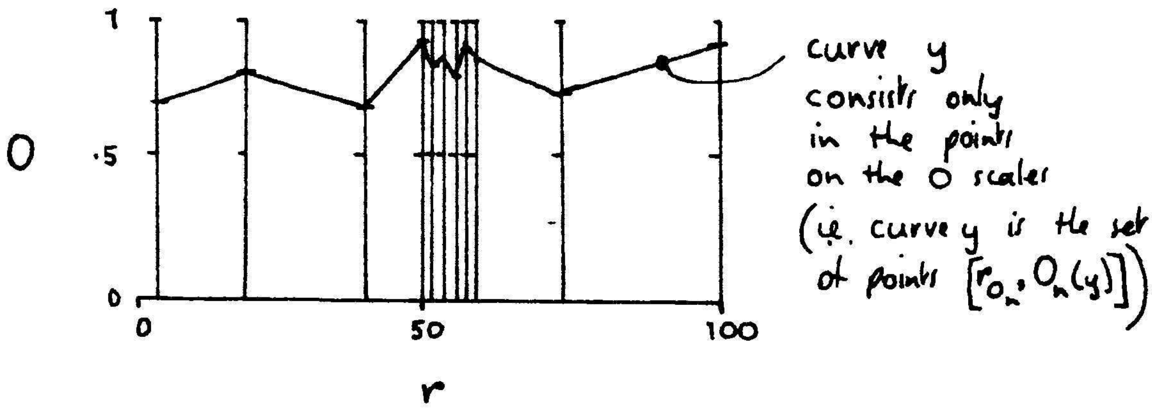
A tendency for a merit curve to lie above its fellow is better than a tendency to lie below

fig 3.20



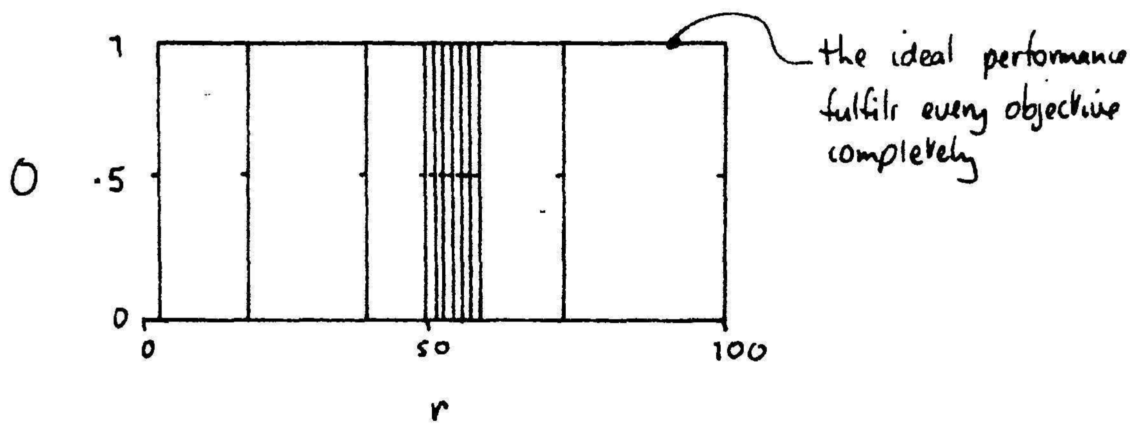
A tendency to a convex curve is better than a tendency to a concave curve

fig 3.22



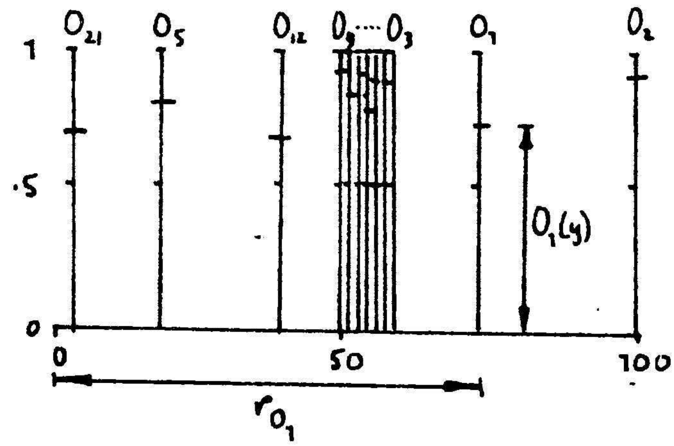
A merit curve consists in the points defined by the degrees of fulfilment of objective and the importance rating of each objective

fig 3.24



The merit curve of an ideal performance consists in the set of points defined by the 'totally fulfilled' end of the objective fulfilment scales

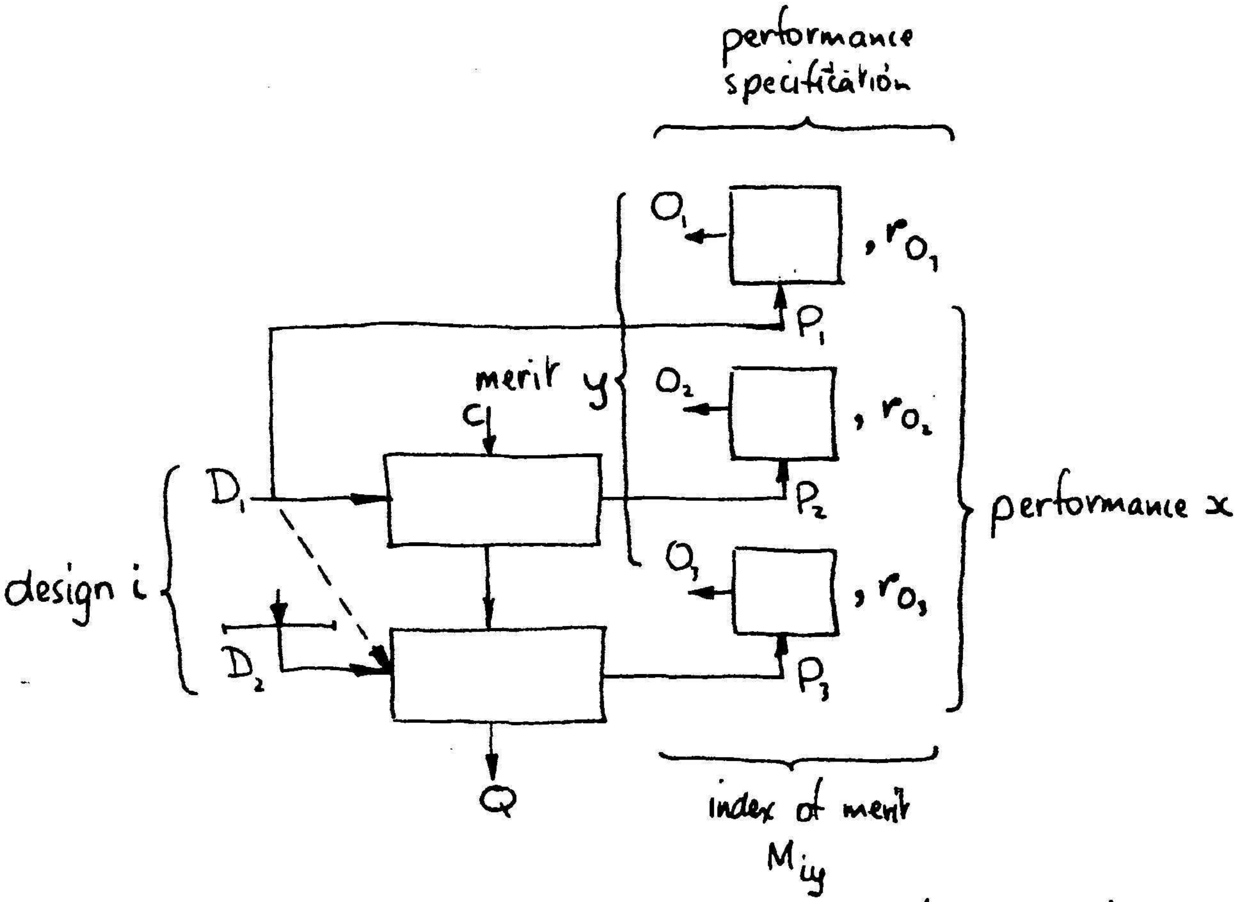
fig 3.25



The index of merit is calculated by:

$$\text{index of merit} = \frac{[r_{O_1} \cdot O_1(y)] + [r_{O_2} \cdot O_2(y)] \cdots + [r_{O_n} \cdot O_n(y)]}{r_{O_1} + r_{O_2} \cdots\cdots + r_{O_n}}$$

fig 3.26



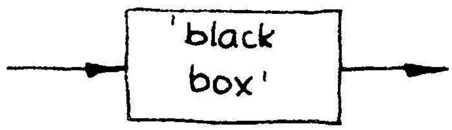
Diagrammatic form of systematic model of a design problem

fig 3.27

systematic model of a multi-objective goal-decision system																		
item	performance specification					decision resource						pro-posal	evaluation of proposal			merit so far		
O_n	$O_n = f P_n$	r_{O_n}	$O_n(y) = f(P_n(l), P_n(u), P_n(x))$			$P_n = f(C_n, D_n)$			$C_n(k)$	$D_n(i) \subset \{D_n(g), \dots D_n(h)\}$			$P_n(x) = f(C_n(k), D_n(i))$	$O_n(y) = f P_n(x)$	$M_{iy}(t) = \frac{\sum(r_{O_n} \cdot O_n(y))}{\sum r_{O_n}}$			
$n_O =$	$n_P =$	$r =$	$l =$	$u =$	$f =$	$n_C =$	$n_D =$	$f =$	$k =$	$g =$	$h =$	$i =$	$x =$	$y =$	$r_{O_n} \cdot O_n(y) =$	$\sum(r_{O_n} \cdot O_n(y)) =$	$\sum r_{O_n} =$	$t =$
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
					1 ·5 0													
					1 ·5 0													

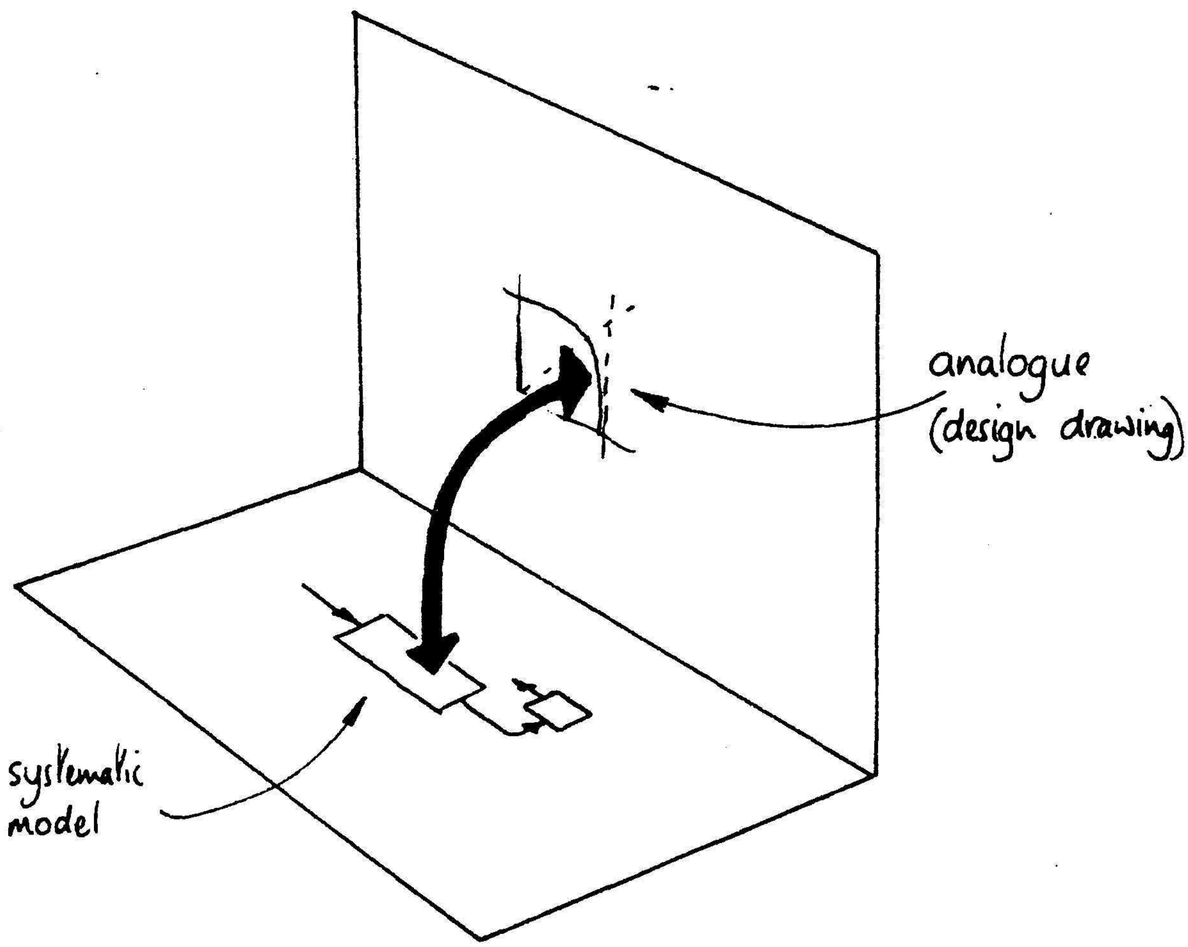
The variables in a systematic model of a goal-decision system may be displayed in the form of a matrix in which, in interplay between the real world and various analogues, the problem may be formulated and a solution developed.

fig 3.28



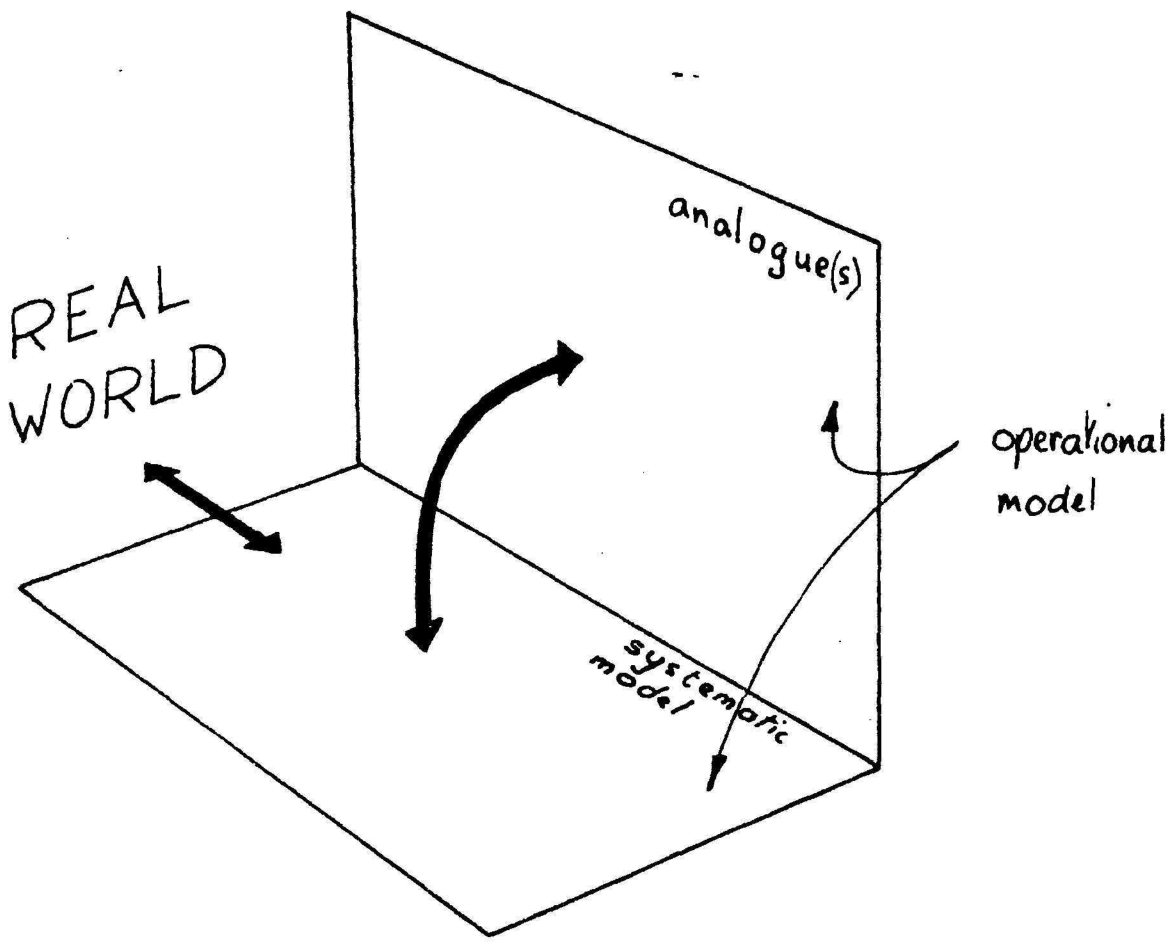
A system in which the mechanism by which the input governs the output may be referred to as a 'black box'.

fig 4.1



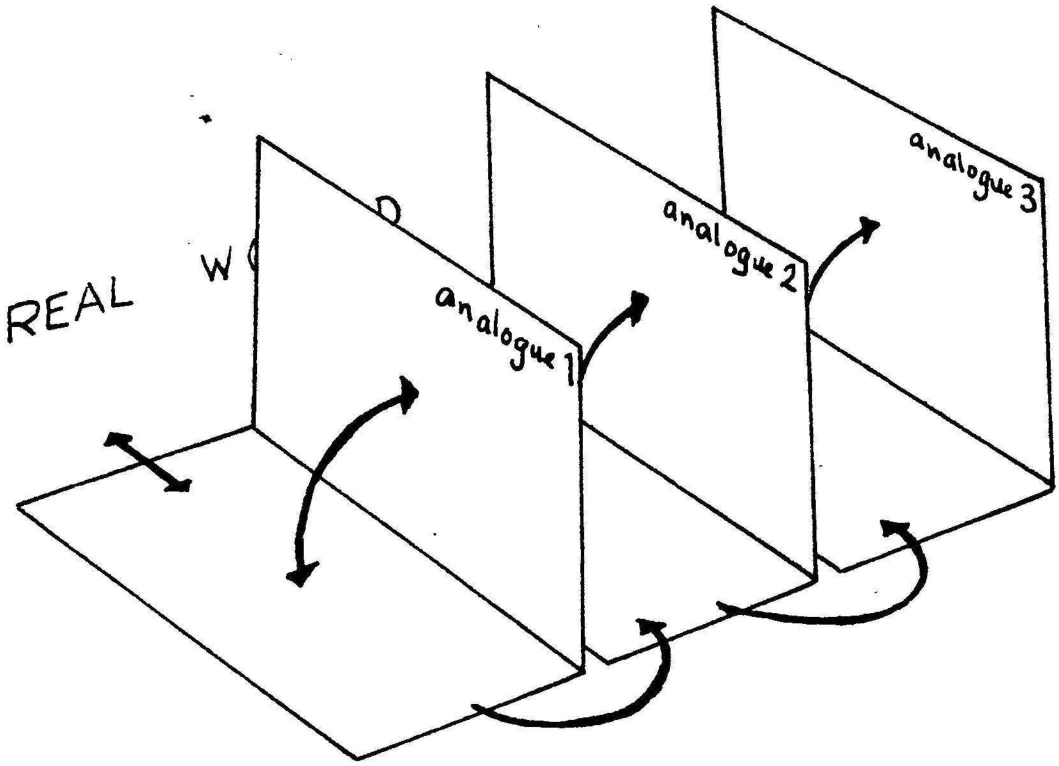
Mathematical, graphical or physical analogues may be employed to predict the effect of given inputs

fig 4.2



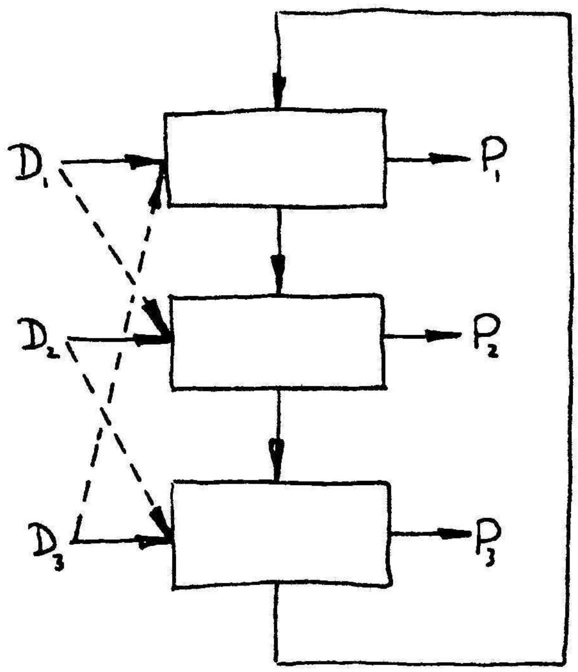
Taken together, the systematic model and one or more analogues constitute an operational model of the real-world problem

fig 4.3



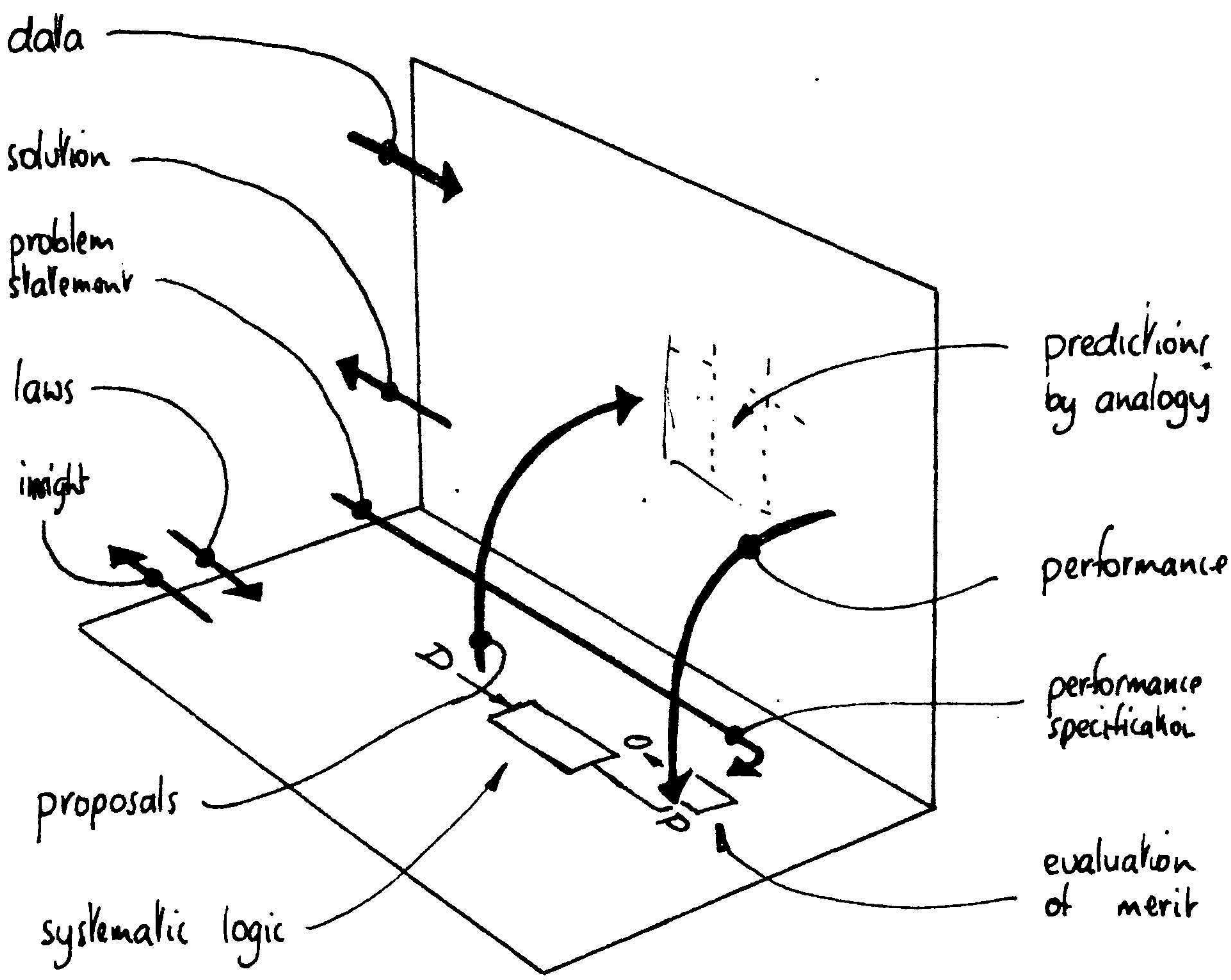
Typically, an overall operational model takes the form of one or more systematic models together with a number of analogues.

fig 4.4



Sometimes a complex system will form a closed loop, each subsystem controlled by an output from another subsystem in the complex

fig 4.5



The design process is a dialogue between the real world and the operational model

fig 4.6

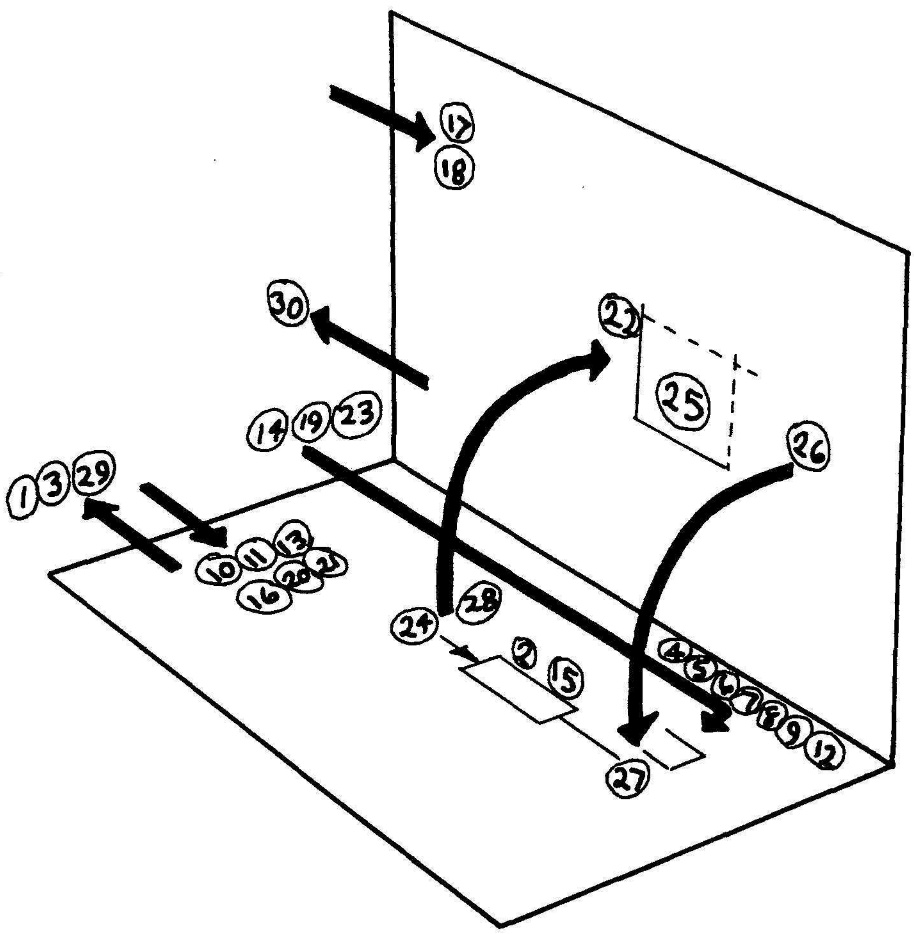
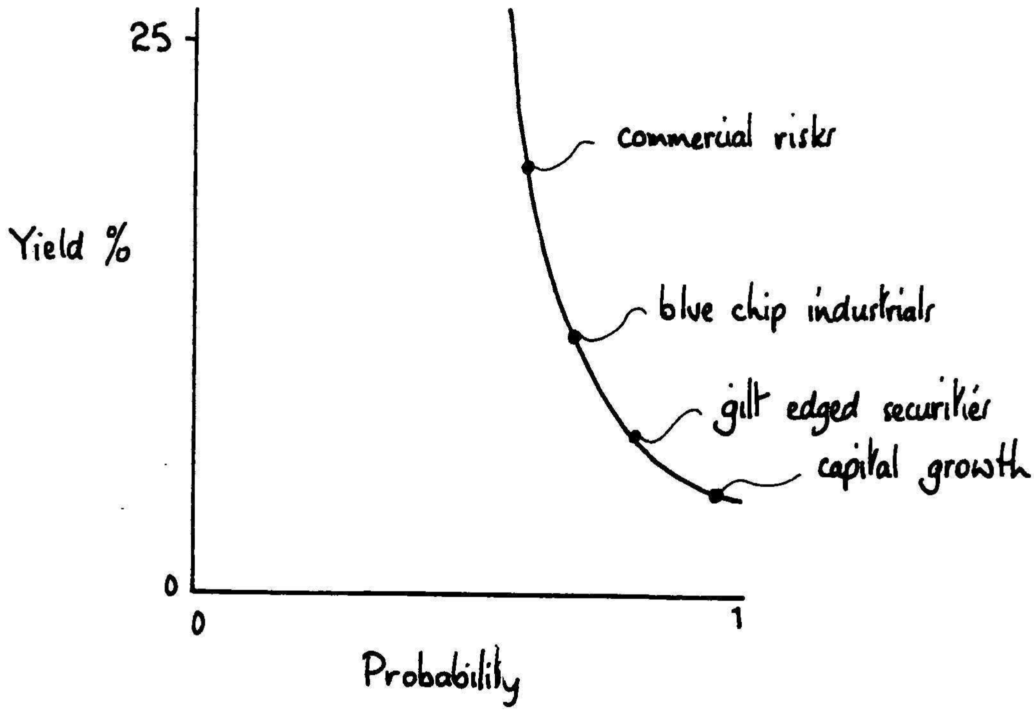


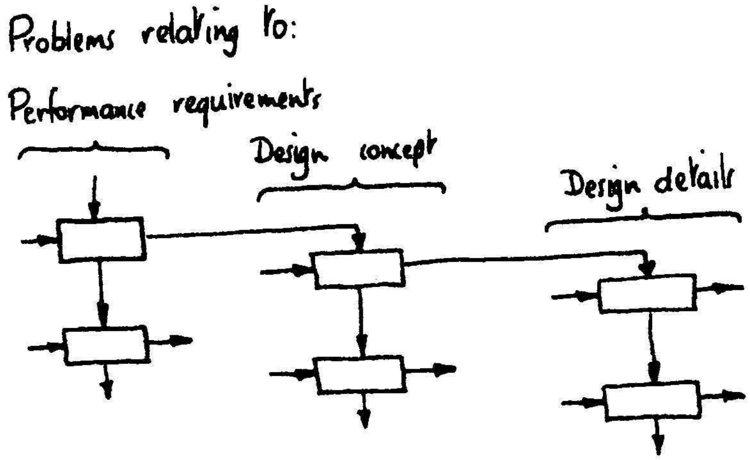
Illustration of a characteristic pattern of movements of a designer between the real-world, his structured concept of that problem, and the analogues he uses in resolving it (for key, see text).

fig 4.7



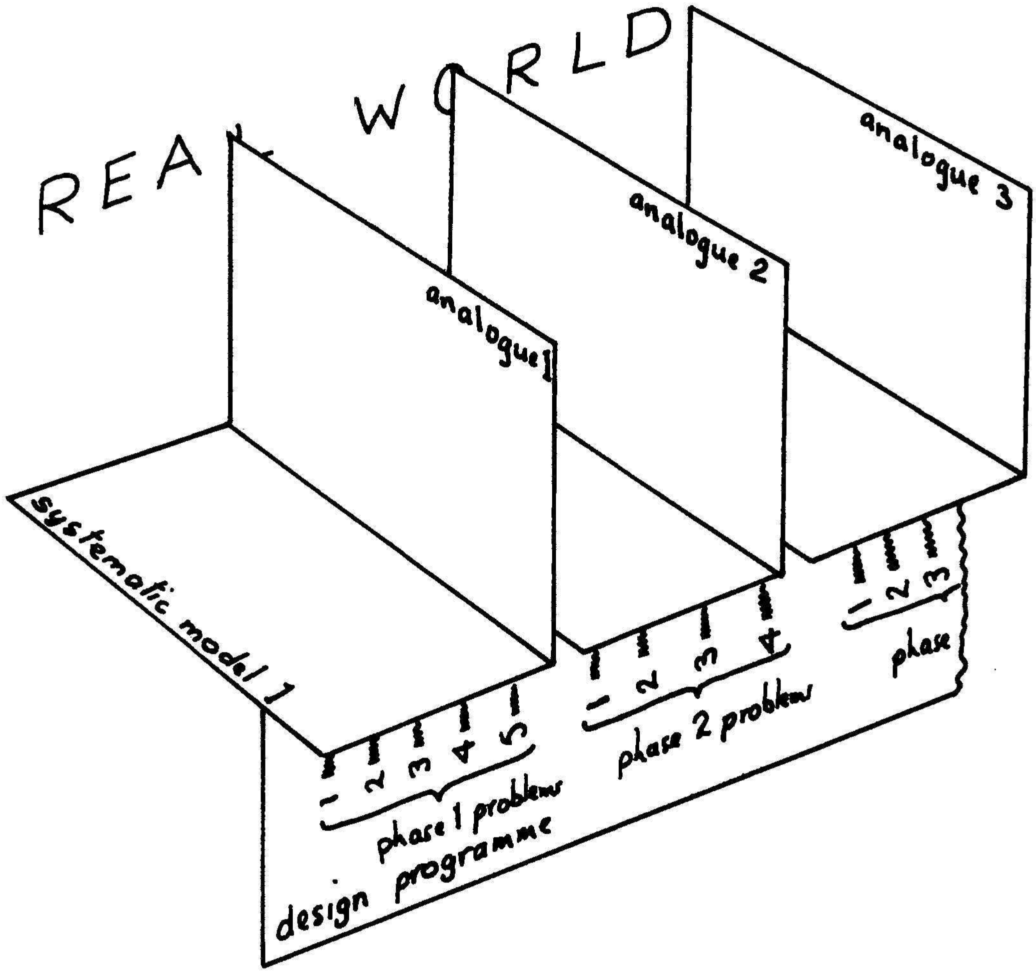
The effect of the interplay of supply and demand on the money market results in higher yields being required on investments subject to higher risks

fig 5.1



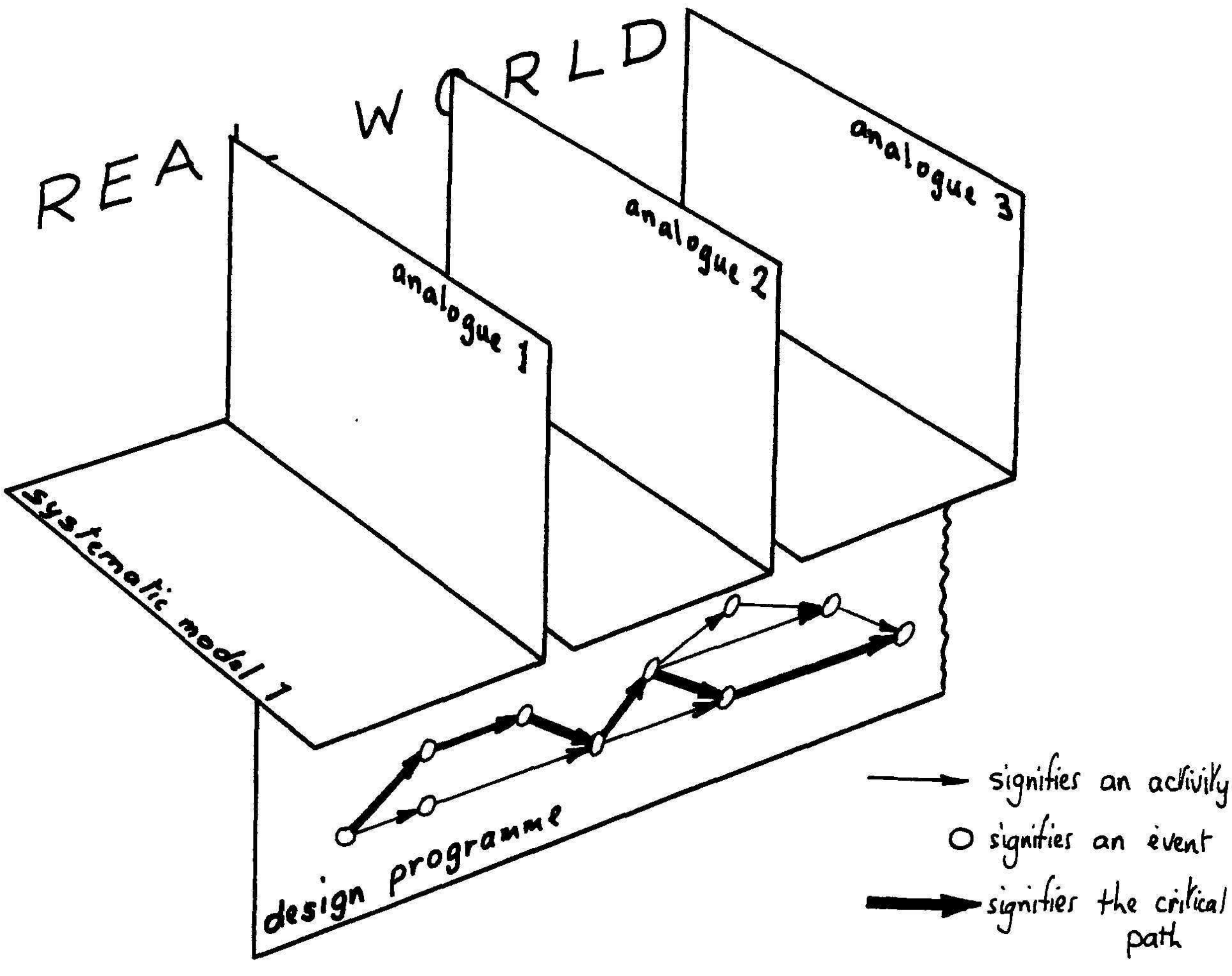
A design project will usually contain a sequence of problems, the results of one stage becoming the context for the next.

fig. 5.2



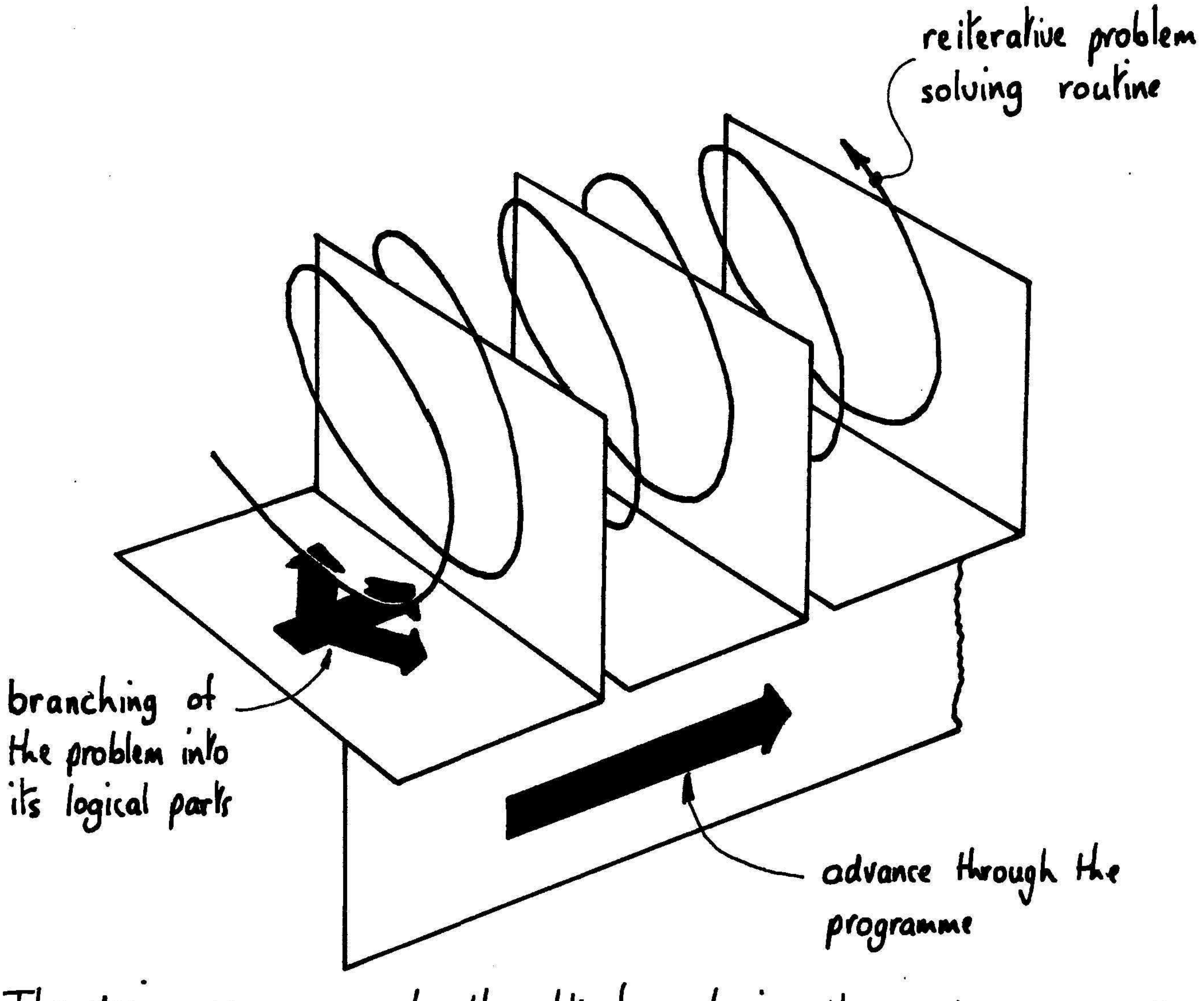
Whilst the systematic models describe the logical relationships of the parts of a problem and the analogues simulate the probable consequences of proposed solutions, the programme indicates the sequential relationships of the activities required to resolve it.

fig 5.3



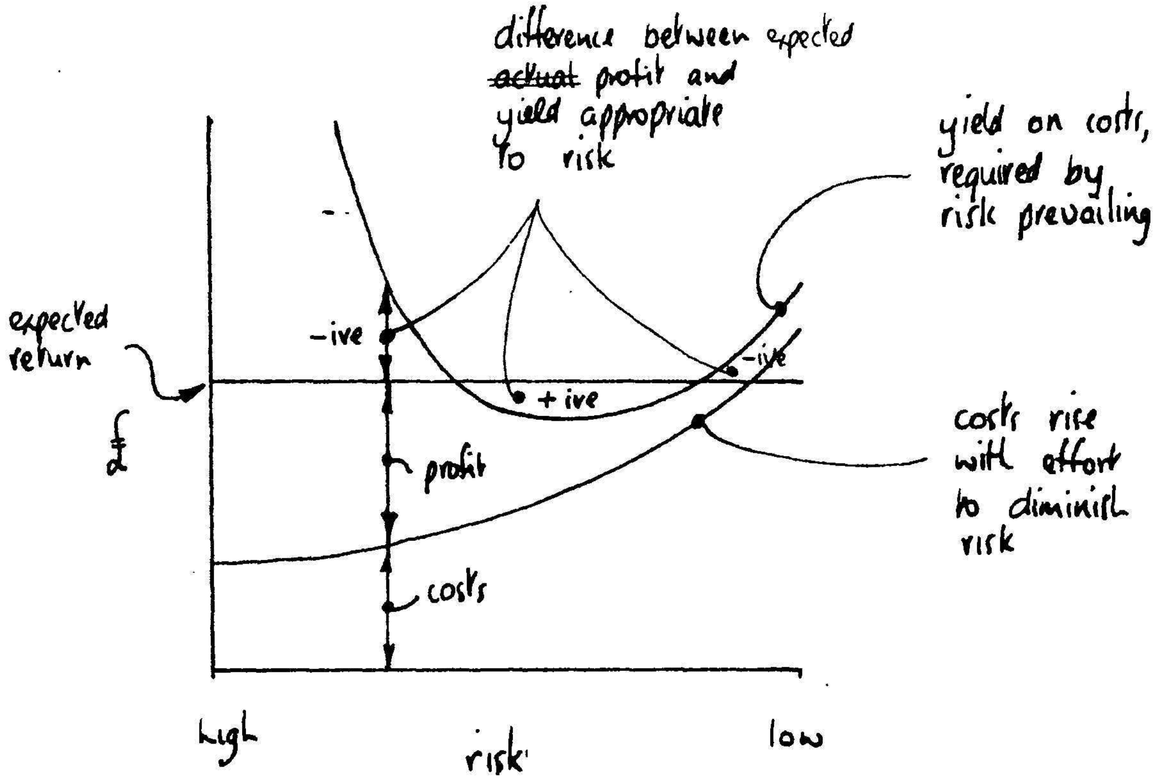
The design programme may be displayed using the conventions of critical path methods

fig 5.4



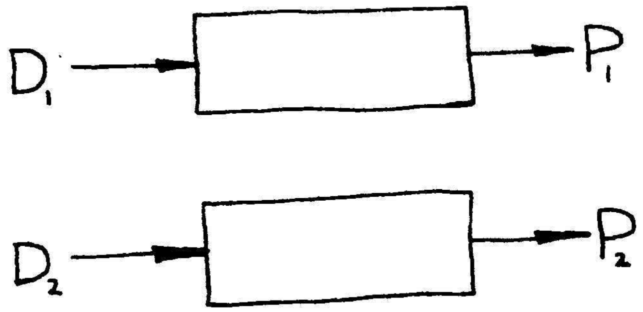
The design process may be thought of as having three main components: the advance through the project and through time, as indicated by the design programme; the branching of the problem into its logical parts, as indicated by the systematic model; and the cyclical problem solving process, described by the reiterative routine.

fig 5.5



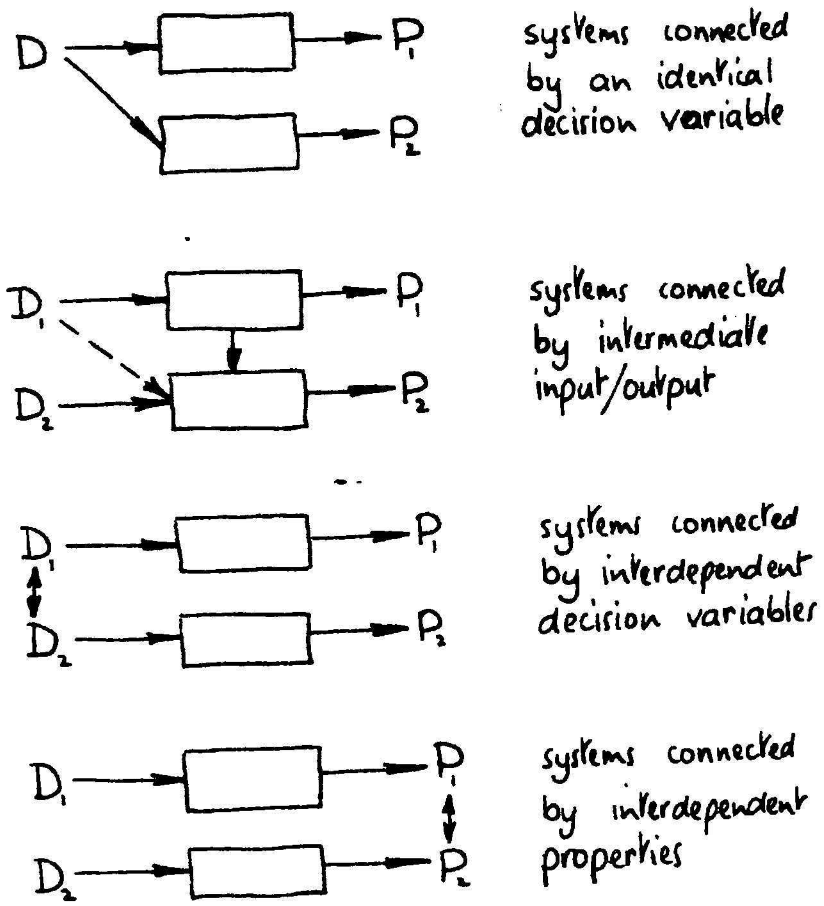
The main function of design management is to sustain a proper balance between the mounting costs of gaining greater certainty and the diminishing profit that the project will yield due to these mounting costs

fig 5.6



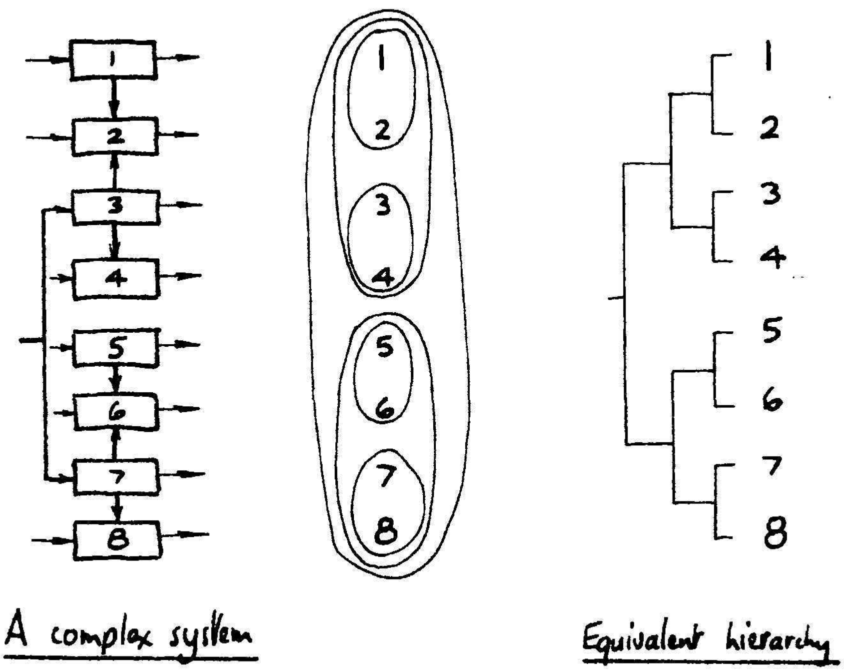
If the output of a system neither affects nor is affected by the variables in another system, the two may be handled as separate problems

fig 6.1



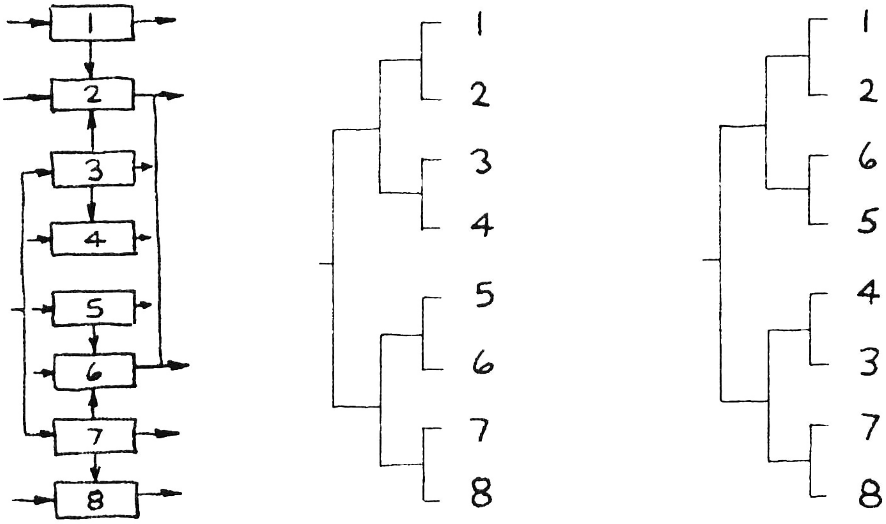
Two goal-decision systems are said to be connected when they have decision variables in common, or when either the decision variables or the properties are interdependent

fig 6.2



A complex of goal-decision systems can be assigned a hierarchy of associations

fig 6.3



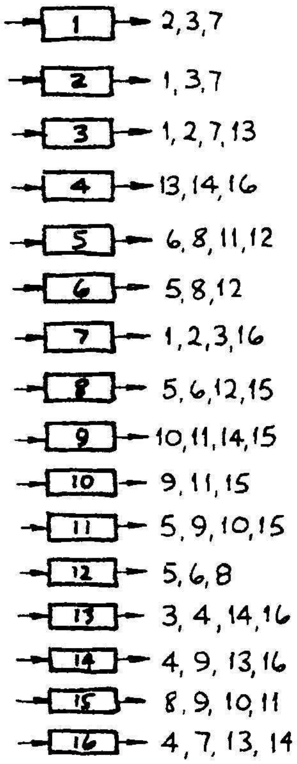
A complex system

Equivalent hierarchy

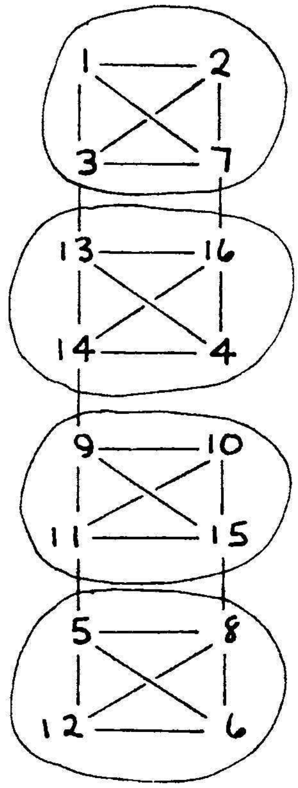
Alternative hierarchy

There may be ambiguity as to the more legitimate or useful pairings in a hierarchy

fig 6.4



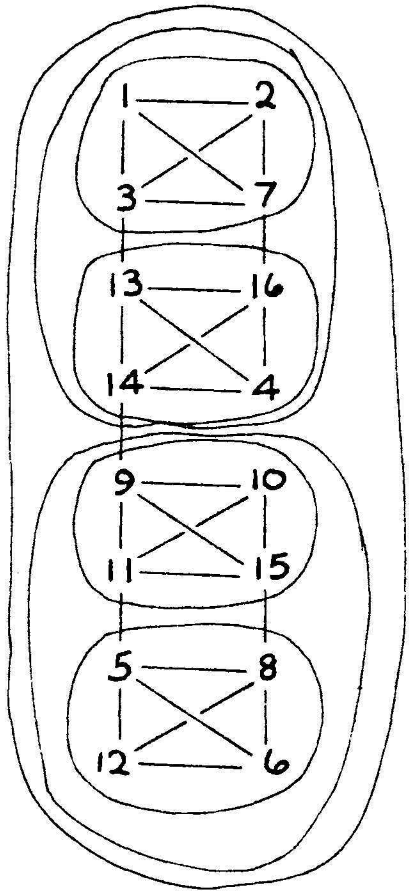
Complex of systems with note of interconnections



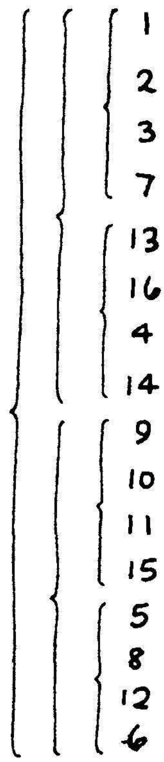
Groupings by richness of interconnection

It is usually possible to distinguish groups of goal-decision systems such that the richness of interconnection within each group is greater than that of any member of the group with systems outside the group

fig 6.5



Groupings by richness of interconnection



Hierarchy of groupings

Interconnected groups can be associated into larger groups and so on in a hierarchy until the whole problem is embraced

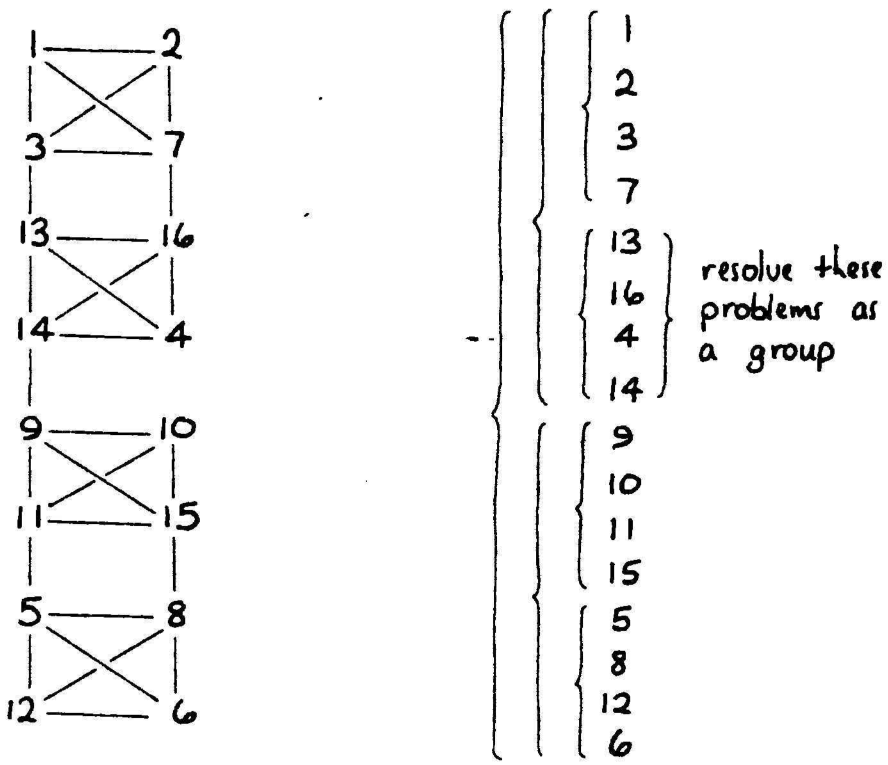
fig 6.6

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	•	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0
2	1	•	1	0	0	0	1	0	0	0	0	0	0	0	0	0
3	1	1	•	0	0	0	1	0	0	0	0	0	1	0	0	0
4	0	0	0	•	0	0	0	0	0	0	0	0	1	1	1	0
5	0	0	0	0	•	1	0	1	0	0	1	1	0	0	0	0
6	0	0	0	0	1	•	0	1	0	0	0	1	0	0	0	0
7	1	1	1	0	0	0	•	0	0	0	0	0	0	0	0	1
8	0	0	0	0	1	1	0	•	0	0	0	1	0	0	1	0
9	0	0	0	0	0	0	0	0	•	1	1	0	0	1	1	0
10	0	0	0	0	0	0	0	0	1	•	1	0	0	0	1	0
11	0	0	0	0	1	0	0	0	1	1	•	0	0	0	1	0
12	0	0	0	0	1	1	0	1	0	0	0	•	0	0	0	0
13	0	0	1	1	0	0	0	0	0	0	0	0	•	1	0	1
14	0	0	0	1	0	0	0	0	1	0	0	0	1	•	0	1
15	0	0	0	0	0	0	0	1	1	1	1	0	0	0	•	0
16	0	0	0	1	0	0	1	0	0	0	0	0	1	1	0	•

1 signifies an interconnection
O signifies no direct connection

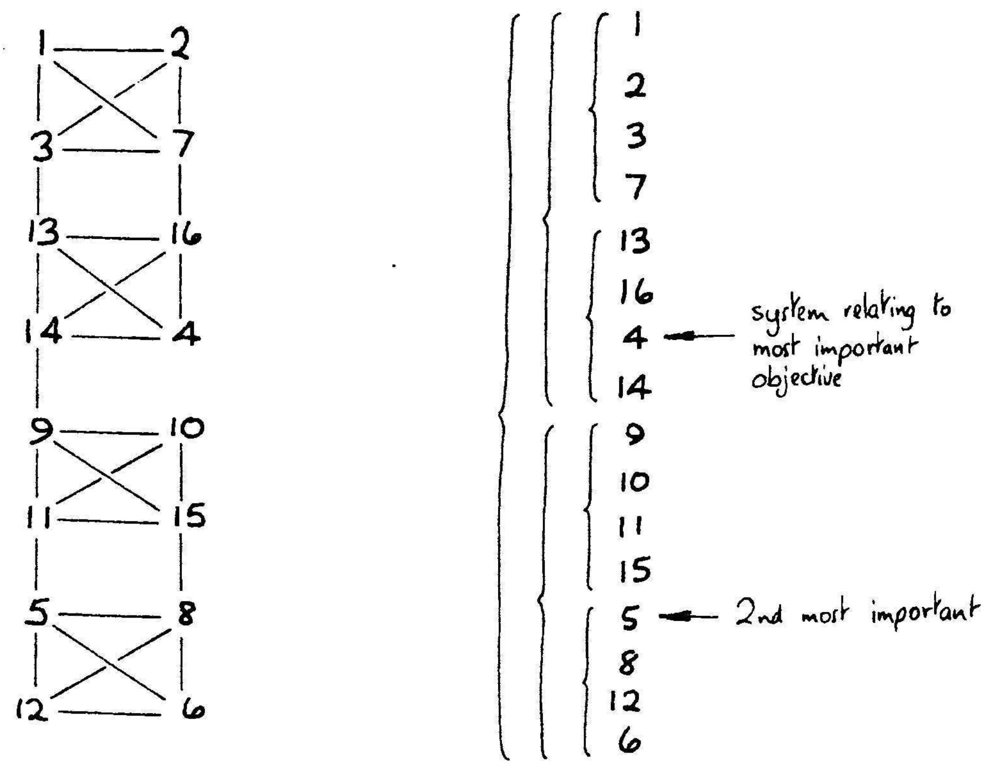
An interaction matrix is a convenient method of recording the interconnections of a complex goal-decision system

fig 6.7



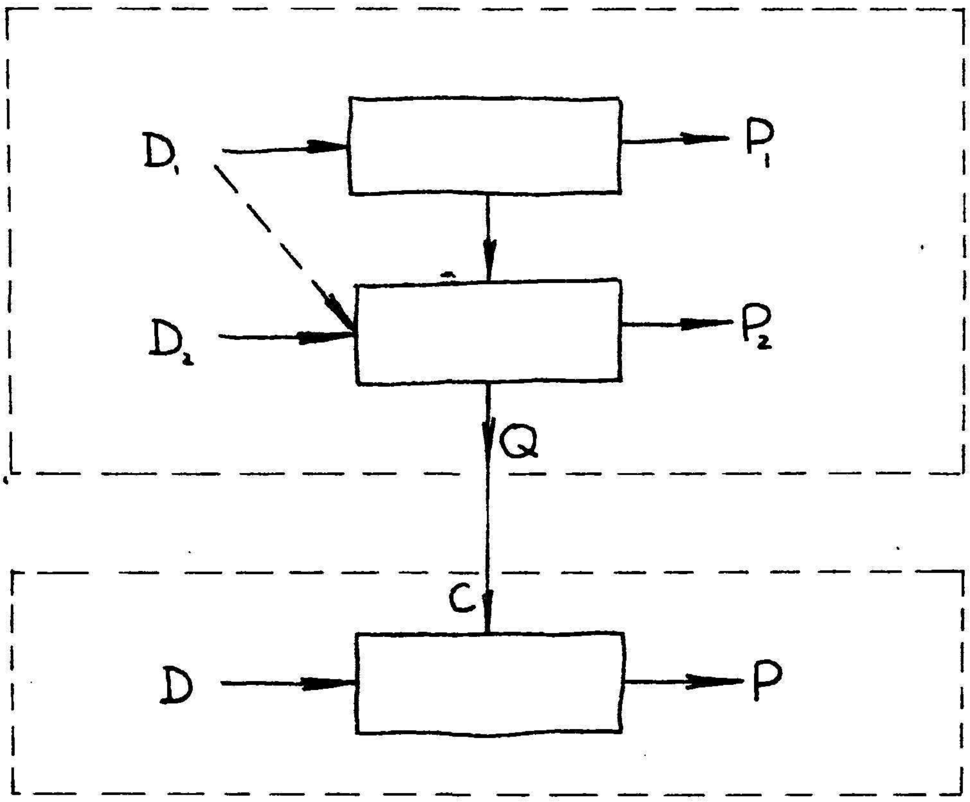
In most circumstances the designer is likely to choose to work on richly interconnected groups of goal-decision systems simultaneously

fig 6.8



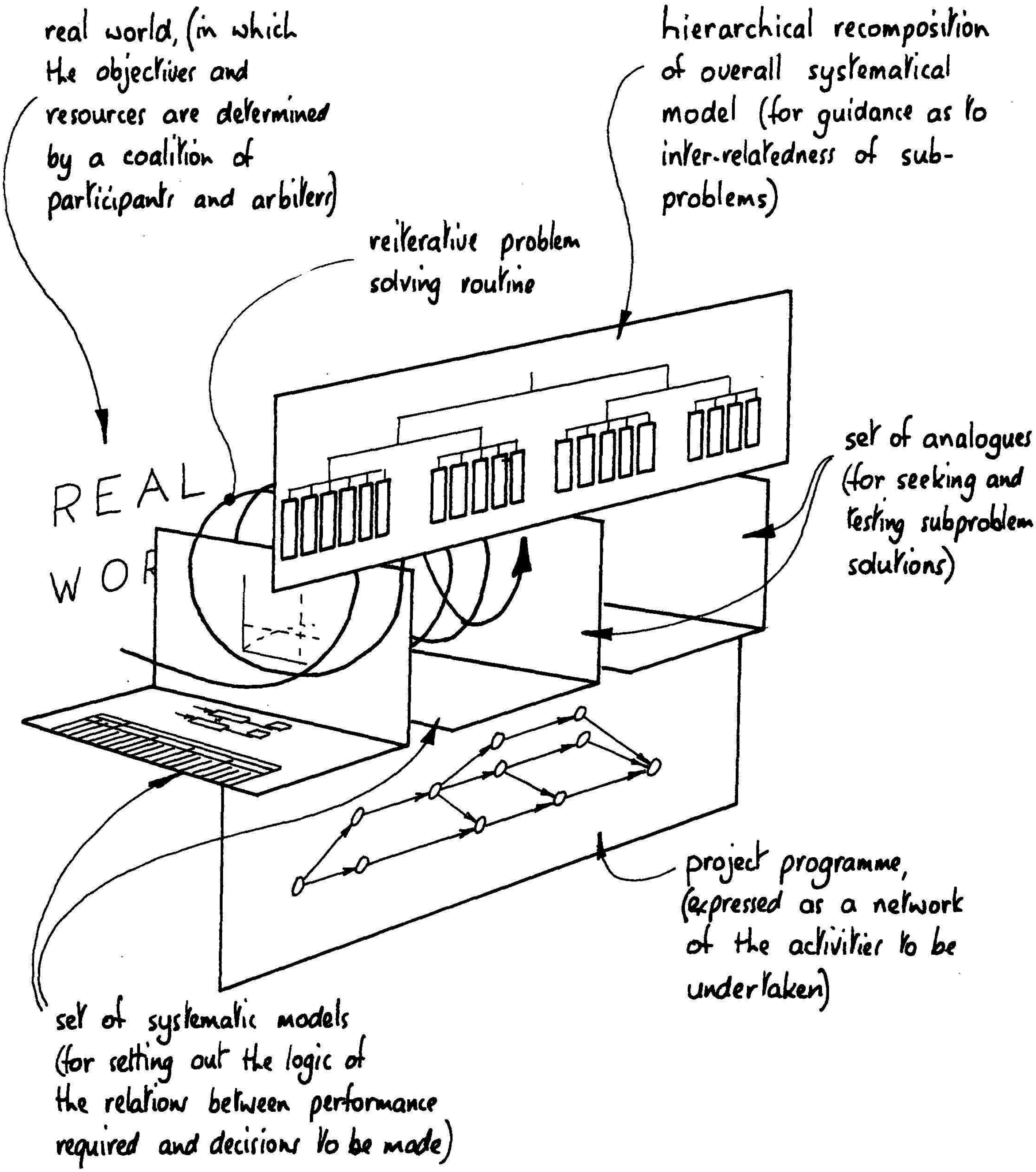
The designer is likely to begin work with the group which contains the goal-decision system relating to the most important objective, then take into account that which relates to the second most important objective, and so on.

fig 6.9



The outputs from one problem field may be the context variables of another. It is a social duty of problem solving participants to guard against possible adverse effects of their decisions on other people's problems

fig 6.10



Design procedure consists in applying a reiterative problem solving routine to a complex of goal-decision systems in accordance with a project programme

fig 6.11

Operational and environmental aspects		C1
usage	influences	existing resources
occasion 1	environment 2	previous designs 3
duration 4	safety 5	existing equipment 6
frequency 7	policies 8	services available 9
sequence 10	test and install 11	experience 12
operators 13	time scale 14	15
maintenance 16	finance 17	18
personnel acceptability 19	manufacture 20	21

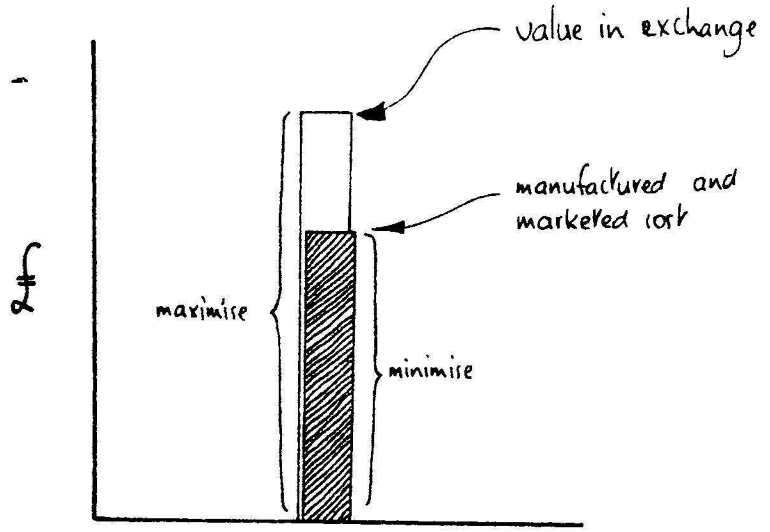
This is one of a series of charts forming part of PABLA (problem analysis by logical approach) published by the Atomic Weapons Research Establishment and based upon a technique developed by the West of England Employers Association

fig 7.1

Parameters (ie. required characteristics)	Parameter steps (ie. means for providing required characteristic)					Remarks
form	circular cylinder	rectangular cylinder	sphere			
size	1 unit	2 units	3 units	4 units		definition of unit required
material	metal	wood	plastic			
orientation	x axis	y axis	z axis			
quantity	1	2	3	4		
speed	low	medium	high			
etc						

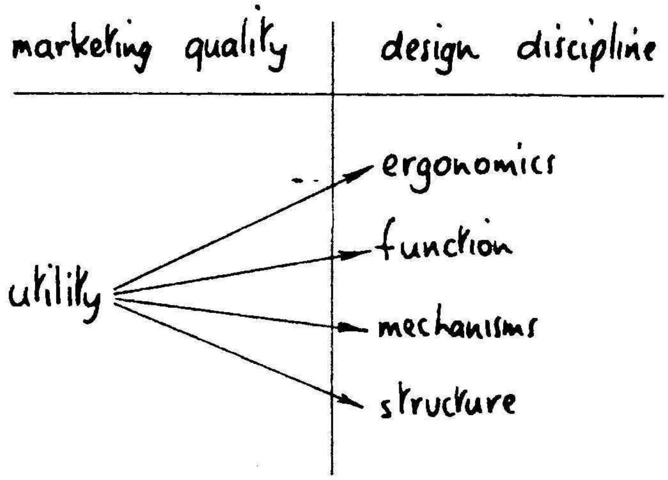
Example of a morphological analysis of means and ends, as developed by K.W. Norris on a principle described by F. Zwicky.

fig 7.2



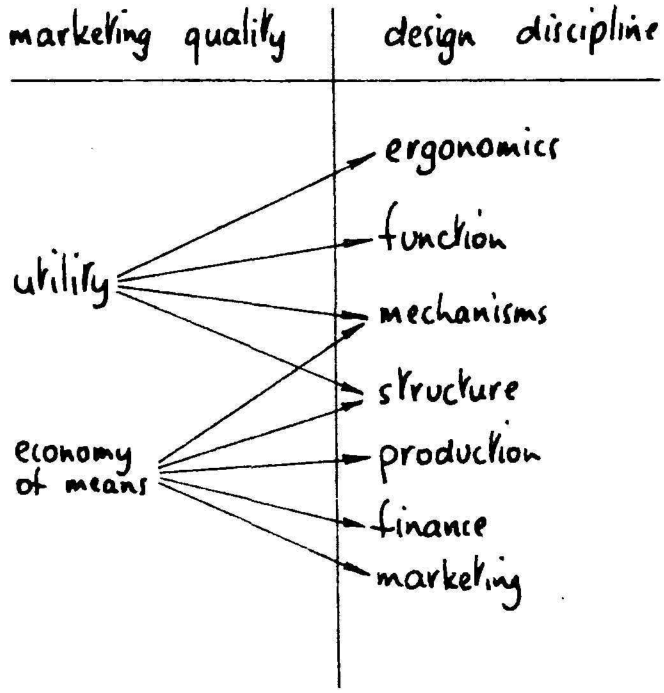
The commercial object of design is usually to maximise value in exchange and minimise the manufactured and marketed cost.

fig 7.3



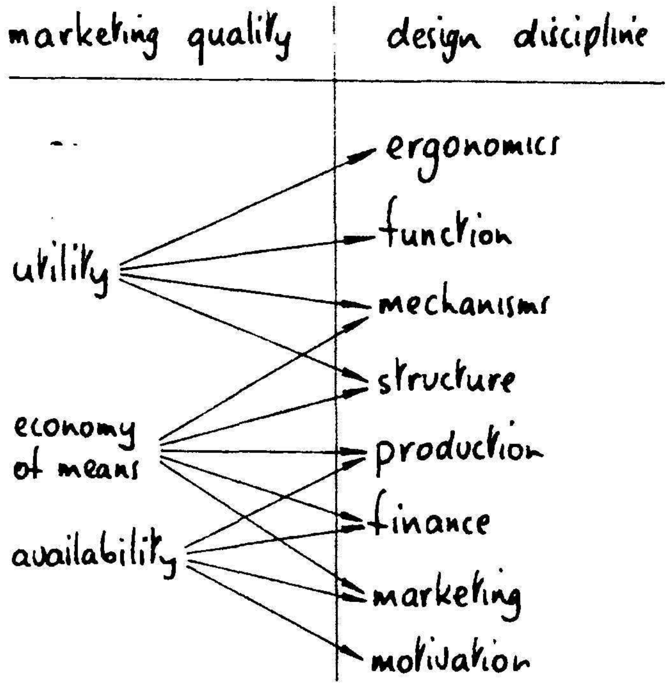
The provision of given commercial qualities in a design arises from the application of various design disciplines

fig 7.4



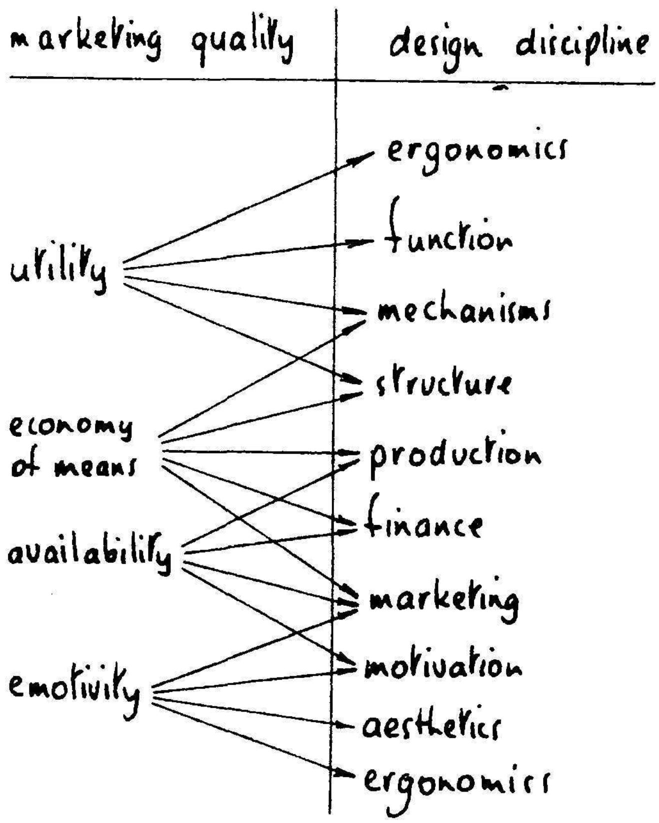
Design disciplines may be concerned with the balance of two or more marketing quality

fig 7.5



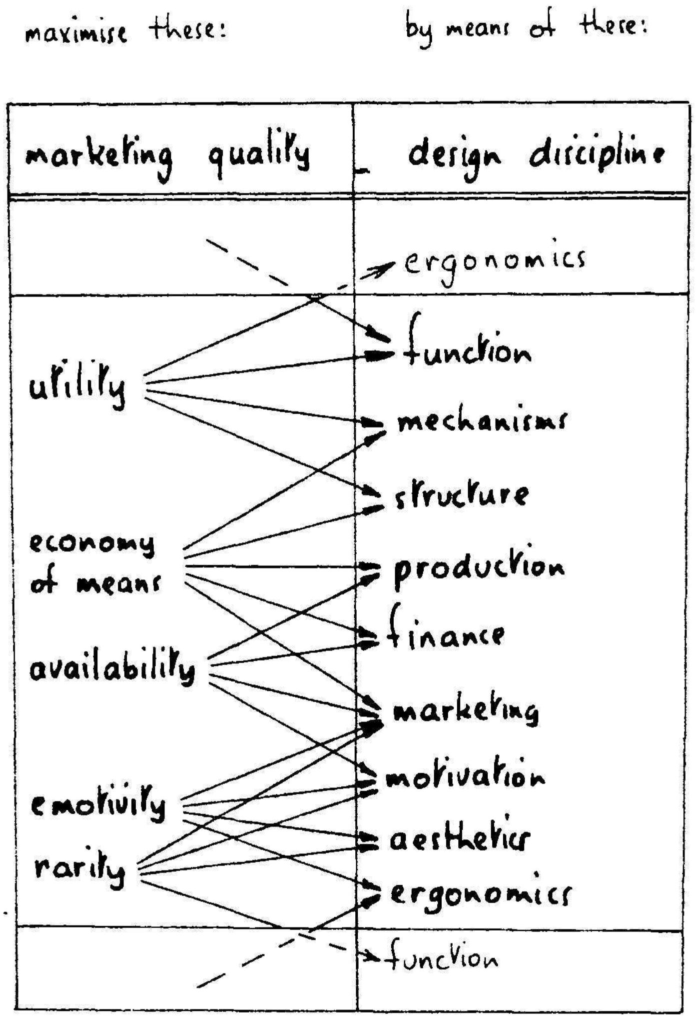
Further design disciplines

fig 7.6



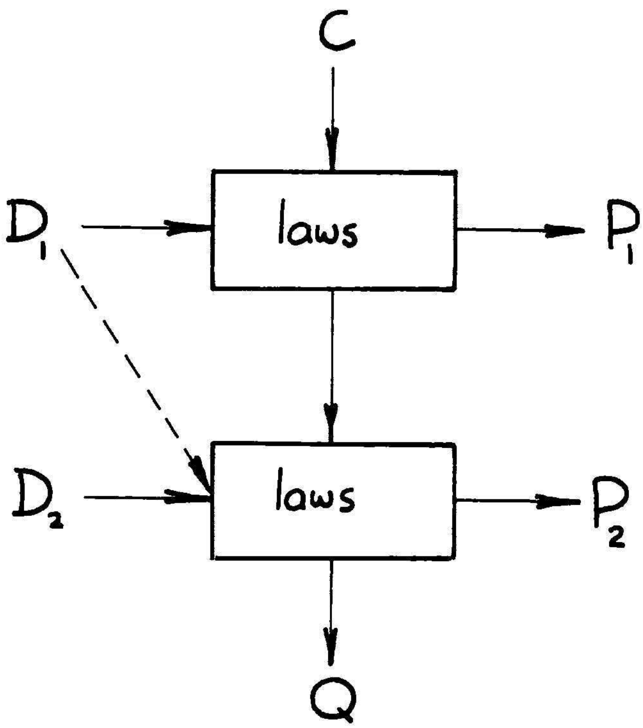
Further design disciplines

fig 7.7



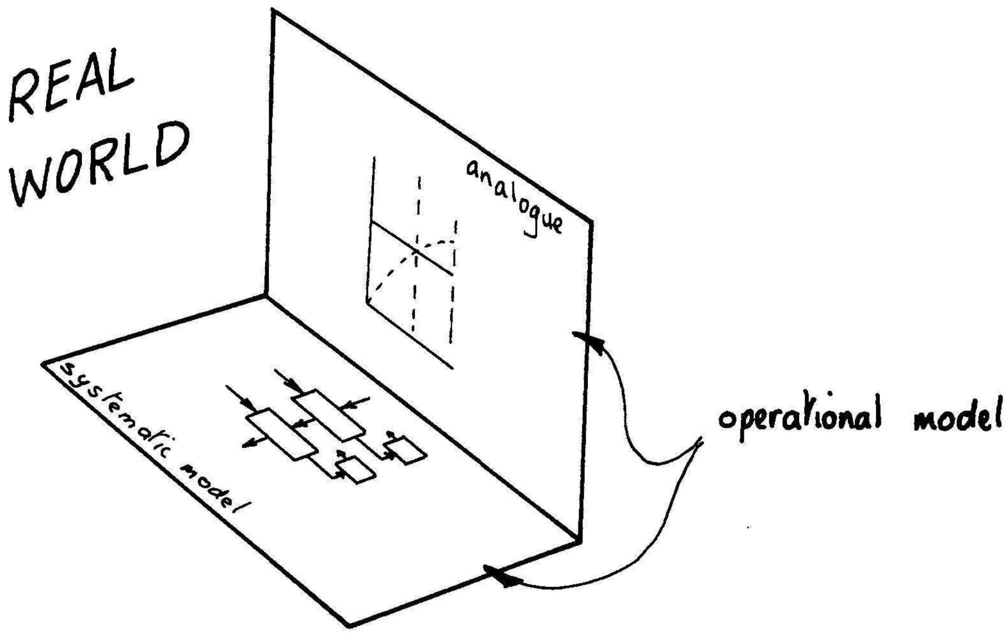
The design disciplines constitute a continuum

fig 7.8



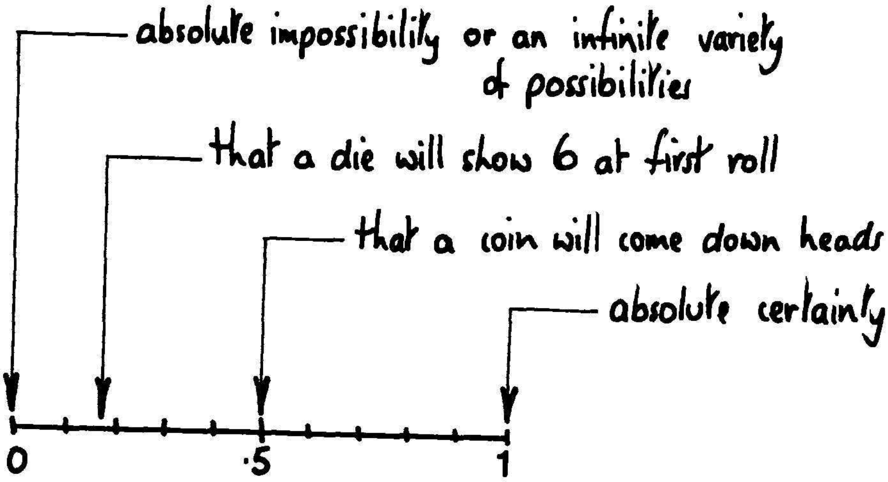
The relationships between the properties and their controlling context and decision variables are governed by laws in the external world

fig 9.1



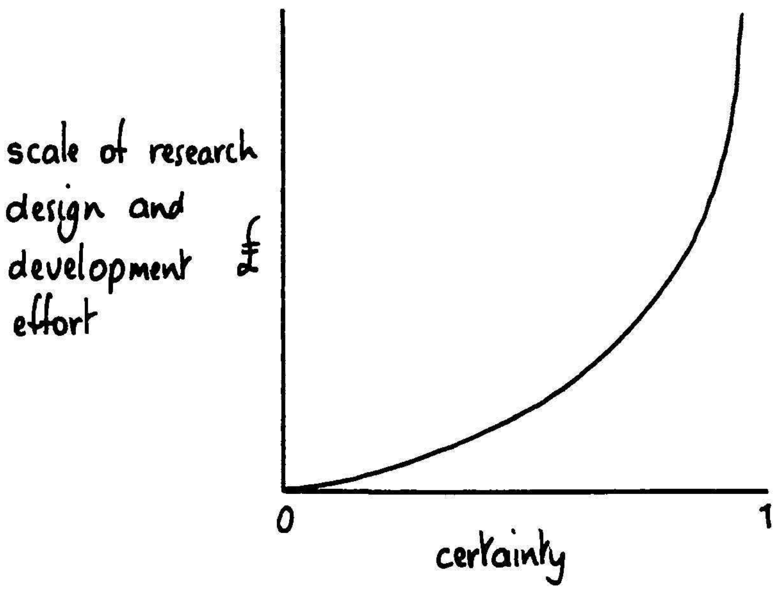
The designer uses operational models to formulate the problem and to predict the outcome in the real world of proposals made by his design

fig 9.2



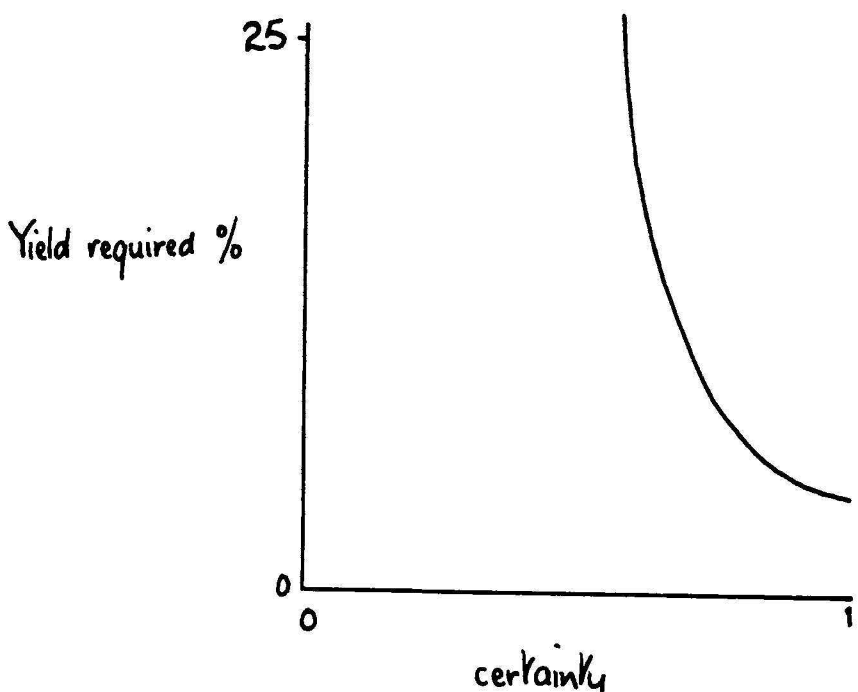
Certainty scale

fig 9.3



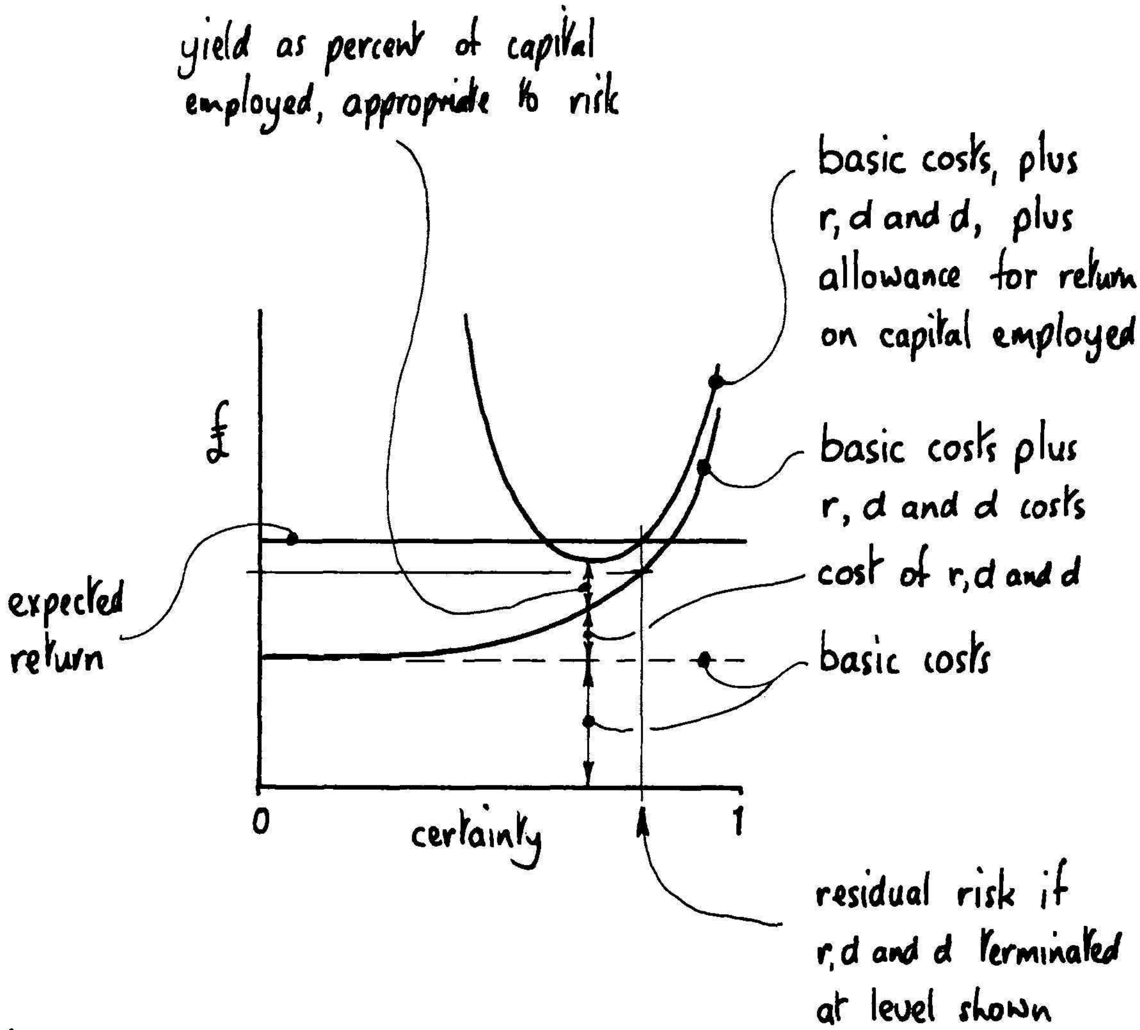
As the research, design and development effort progresses, so the uncertainty about the nature of the requirements and the effectiveness of the end product is reduced.

fig 9.4



The yield, as a percentage of capital employed, is required to relate to the degree of risk attached to it.

fig 9.5



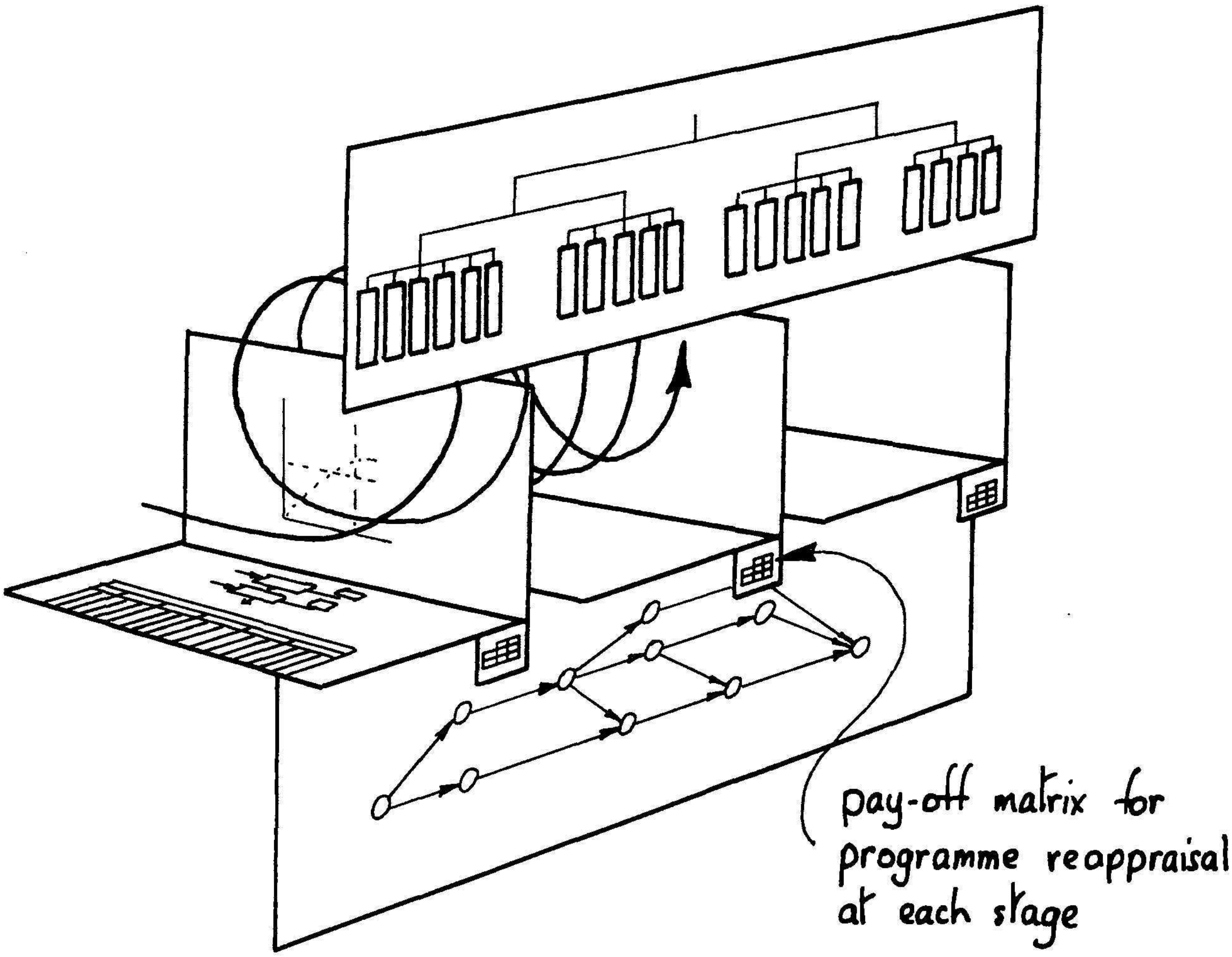
The research, design and development activity should not normally be continued beyond the point when total costs, including an allowance for a return on capital appropriate t the risk involved, match the expected return.

fig 9.6

		possible outcome		
		u	w	x
proposal	h	M =	M =	M =
	i	M =	M =	M =
	j	M =	M =	M =

A pay-off matrix sets out the merits of the various possible outcomes associated with alternative proposals, to simplify selection

fig 9.7



The expediency of continuing, and of alternative courses of action, must usually be appraised at each stage

fig 9.8

Marginal references ....

marginal ref. 1

As indicated by the context of references in the Daily Telegraph, representing 'serious' national daily newspapers, and in the Daily Mirror, representing 'popular' national daily newspapers, during 1966.

marginal ref. 2

As indicated by the context of references in he Architects' Journal, Design, The Designer and The Engineering Designer during 1966.

marginal ref. 3

Engineering design: a report of a committee appointed by the Council for Scientific and Industrial Research to consider the present standing of mechanical engineering design, Her Majesty's Stationery Office, 1963.

marginal ref. 4

Constitution, International Congress of Societies of Industrial Design, 1959.

marginal ref. 5

The unavoidability of reference to a value system in defining objectives is well argued on p. 29 of I.D.J. Bross's Design for decision, Macmillan, 1953. The terms used in the present paper also owe a great deal to those used in Horst Rittel's The universe of design, University of California, Berkeley, 1966.

marginal ref. 6

Somewhat similar definitions and notation are used in separate chapters by Russell L. Ackoff and C. West Churchman in Progress in operations research, volume 1, Wiley, 1961 (Russell L. Ackoff, editor). See also Games and decisions by Luce and Raiffa, Wiley, 1957, considered by some to be the best work on value theory.

marginal ref. 7

This is simply the expression for a straight line graph passing through P(l) and P(u). P(l) and P(m) are interchangeable in this formulation, and either term may be employed, to suit the context of the problem.

marginal ref. 8

This, and the following rather unweildy formulations, describe typical property/satisfaction curves. In practice, it is usually easier simply to draw the curve most appropriate to the circumstances, and to read off, rather than to calculate, the merit indices associated with given values of P.

marginal ref. 9 — The rankable, rather than the quantifiable, basis of perceptual and aesthetic criteria is argued by E.H. Gombrich in his book Art and Illusion, Phaidon, 1956.

marginal ref. 10 — Russell L. Ackoff, in Scientific method: optimising applied research decisions, Wiley, 1962, describes design problems as falling into the general class of developmental problems, which he defines similarly.

marginal ref. 11 — A study of the validity of subjective scaling, carried out by Dr. Samuel J. Messick at the University of Illinois, is referred to by Osgood, Tannenbaum and Suci on p. 146 of their The measurement of meaning, University of Illinois Press, 1957. In another paper (E. Adams and S. Messick, An axiomatic formulation and generalisation of successive intervals scaling, Psychometrika, 1958, 23, pp. 355-68) many ordinal scale models and validity tests are listed, and a technique presented for the testing of the consequences of assumptions about successive ordinal scales. C.H. Coombs, in Psychological scaling without a unit of measurement, Psychological Review, Vol 57, May 1950, No 3, introduces an 'ordered metric scale' derived from the relationship between a subjective scale and an associated physical scale.

marginal ref. 12 — This invokes the technique of linear programming. See S. Vajda's An introduction to linear programming and the theory of games, Methuen, 1960, and/or G.B. Dantzig's Linear programming and extensions, Princeton University Press, 1963. See also the AIDA technique (analysis of interconnected decision areas), referred to on p. 27 of Interdependence and uncertainty, Tavistock Publications, 1966.

marginal ref. 13 — Ludwig von Bertalanffy, in his paper General systems theory (Human Biology, 1951) argued that all human societies, or segments of it, are essentially goal-seeking open systems. See also paper on Individual motives and group goals in Group dynamics - research and theory by Cartwright and Zander, Row Peterson and Co, 1962.

Marginal references

marginal ref. 14

For an admirably clear statement of the systems idea, see Introduction to Cybernetics, W. Ross Ashby, Chapman & Hall, 1957. ee also General systems theory: Skeleton of a science, K.E. Boulding, Management Science, April 1956, and An approach to cybernetics, Gordon Pask, Hutchinson, 1961.

marginal ref. 15

Norbert Wiener's exposition in Cybernetics, Wiley, 1948, of the concept of 'feedback' as a principle of control, common to machines, animals and human beings, formed the basis of modern systems theory.

marginal ref. 16

This is demonstrated for general problems by Russell L. Ackoff in Scientific method: optimising applied research decisions, Wiley, 1962, and by Miller & Starr in Executive decisions and operations research Prentice Hall, 1960. For design problems it is demonstrated by Hugh M. Bowen in a series of articles on Rational design in seven successive issues of Industrial Design, commencing February 1964.

marginal ref. 17

This distinction between the situation in the real world and the problem solver's mental concept of what might be done in that real world is studied on p. 372 of Russell L. Ackoff's Scientific method: optimising applied research decisions, Wiley, 1962.

marginal ref. 18

This is well-demonstrated in Executive decisions and operations research, David W. Miller and Martin K. Starr, Prentice Hall, 1960.

marginal ref. 19

The point that the selection of objectives necessarily involves a more or less arbitrary decision, based upon an individual's set of values, somewhere along the line is clearly argued by David W. Miller and Martin K. Starr in Executive decisions and operations research, Prentice Hall, 1960. The repeatability of subjective measurement is demonstrated by S.S. Stevens in On the theory of scales of measurement, Science 1946, 103, 677-80; by E. Adams and S. Messick in An axiomatic formulation and generalisation of successive intervals scaling, Psychometrika 1958, 23, 355-68; and by Clyde H. Coombs, in Psychological scaling without a unit of measurement, Psychological Review, vol. 57, May 1950, 145-158.

marginal ref. 20 — But see also certain qualifications set out in para. 329.

marginal ref. 21 — In order to provide room for manoeuvre in seeking an optimum solution, and indeed in order to maximise the probability of obtaining an arena for a solution at all (see para. 2.27), the low limits of acceptability must be set at that threshold below which performance would really be quite unacceptable.

marginal ref. 22 — For example, see figs. 6.3 to 6.6.

marginal ref. 23 — Stafford Beer, in Cybernetics and Management, English Universities Press, 1959, argues that in 'black box' situations the use of models is the only alternative to systematic meddling with the real world system.

marginal ref. 24 — See A guide to operational research, Eric Duckworth, Methuen, 1962, and The universe of design, Horst Rittel, Institute of Urban and Regional Development, University of California, Berkley.

marginal ref. 25 — The general case, as distinct from the special case of the design problem, is set out in W. Ross Ashby's Introduction to cybernetics Chapman & Hall, 1957.

marginal ref. 26 — This pattern is seen in the behaviour of designers engaged with problems, whether their method of working is self-consciously controlled or not.

marginal ref. 27 — An interesting description of the relations between the participants in a problem solving activity, using sociological and communications theory models, is given on pp. 36, 39 of Interdependence and uncertainty: digest of a report from the Tavistock Institute, Tavistock Publications, 1966.

marginal ref. 28 — Or alternatively, at any given yield, capital will tend to flow to those investments which offer the least risk. See Investment appraisal, National Economic Development Council, Her Majesty's Stationery Office, 1967.

marginal ref. 29

See Plan of work, reprinted from Handbook of architectural practice and management, Royal Institute of British Architects, 1967; A code of procedure for selective tendering, National Joint Consultative Committee for Architects, Quantity Surveyors and Builders, 1965; and Building project management, National Joint Consultative Committee for Architects, Quantity Surveyors and Builders, 1963.

marginal ref. 30

Numerous model product development programmes have been set out by various authors, for example L. Bruce Archer, Morris Asimow, Hugh M. Bowen, J. Christopher Jones, R.J. McCrory, E. Matchett, and Martin K. Starr (see bibliography 5).

marginal ref. 31

A lucid explanation and attractive approach to critical path methods is contained in A. Battersby's Network analysis for planning and scheduling, Macmillan, 1964. See also K. Lockyer's Critical path analysis, Pitman, 1964. A model design programme in network form is given by L. Bruce Archer in Systematic method for designers, Council of Industrial Design, 1966.

marginal ref. 32

See Stafford Beer's Cybernetics and management, English Universities Press, 1959.

marginal ref. 33

Some aspects of the relationship between the intensity of a problem and uncertainty, mainly in connection with the design and construction of buildings, are discussed on p. 17 of Interdependence and uncertainty: digest of a report from the Tavistock Institute, Tavistock Publications, 1966.

marginal ref. 34

This model programme is based mainly upon examination of the case studies listed in the appendix.

marginal ref. 35

Marketing considerations will also have figured largely in Phases 1 and 2, of course.

marginal ref. 36 — See Robert Leduc's How to launch a new product, Crosby Lockwood, 1966, Edgar A. Pessemier's New product decisions: an analytical approach, McGraw Hill, 1966, and R. Schlaifer's Probability and statistics for business decisions, McGraw Hill, 1959.

marginal ref. 37 — It is interesting to note that Miller & Starr, in Executive decisions and operations research, Prentice Hall, 1960, define the moment when a creative act e.g. design is called for as "when the saddlepoint in a payoff matrix is negative", that is to say, when the best that can be done within existing resources is inevitably at a loss.

marginal ref. 38 — H.A. Simon refers to the decomposition of decision networks in The new science of management decision, Harper, 1960. A very lucid argument on the application of these principles to design is contained in Christopher Alexander's Notes on the synthesis of form, Harvard University Press, 1964, although Alexander's technique for the recomposition of designed elements into a whole design can be questioned.

marginal ref. 39 — See

marginal ref. 40 — For an outline of the theory of games, see p. 38 of Eric Duckworth's A guide to operational research, Methuen, 1962. For a detailed account, see J.D. William's The compleat strategyst, McGraw Hill, 1954 or Luce and Raiffa's Games and decision, Wiley, 1957.

marginal ref. 41 — A similar description of the role of participants is contained in Interdependence and uncertainty: digest of a report from the Tavistock Institute, Tavistock Publications, 1966. See also papers on "Individual motives and group goals" and "The structural properties of groups" in Group dynamics: research and theory, Cartwright and Zander (editor), Row Petersen, 1962.

marginal ref. 42 — Chance and natural phenomena are, in a sense, the outcome of the 'games of the gods'.

<u>marginal ref. 43</u>	That is, until we introduce a system of human values (see next para.). This is the basis of linear programming, see 'Linear programming' by A. Baines and K.B. Haley in <u>Operational research in management</u>, R.T. Eddison, K. Pennycuick and B.H.P. Rivett (editors) English Universities Press, 1963.
<u>marginal ref. 44</u>	The man-machine-environment idea as a design tool is described in W. Ross Ashby's <u>Introduction to cybernetics</u>, Chapman and Hall, 1957. The method study approach, closely based upon that developed by the West of England Employers' Association, in which four basic charts are used to provide a check list of questions of the "What, why, where, when, who and how?" variety, is set out in <u>Problem analysis by logical approach (PABLA)</u>, published by the Atomic Weapons Research Establishment 1965.
<u>marginal ref. 45</u>	Some case studies of the application of morphological analysis techniques to design problems have been described by K.W. Norris in <u>Conference on design methods</u>, J. Christopher Jones (editor), Pergammon, 1963.
<u>marginal ref. 46</u>	Adequately recorded case studies are rare in the design field. In recent years architects in particular have begun to publish check lists of factors to be taken into account in particular classes of buildings.
<u>marginal ref. 47</u>	All design must ultimately face the acid test of detailed scheduling and manufacture, of course. Most designers pursue a mixed strategy, dealing in the abstract with the most pressing or most accessible problems and proceeding to deal empirically with the remainder.
<u>marginal ref. 48</u>	Even in non-commercial circumstances the cost/value relationship is important. Whether on a company, an industry or a national level, a net gain in wealth is necessary. It is on the question of the distribution of the wealth produced that economic and politico-economic questions revolve.

marginal ref. 49 — This idea forms the opening paragraphs of almost any standard work on economics. An interesting commentary on this relationship between price, utility and human values appears on pp. 240-4 of J.B. Cooper's and J.L. McGaugh's Integrating principles of social psychology, Schenkman, 1963.

marginal ref. 50 — Again, see J.B. Cooper and J.L. McGaugh, Integrating principles of social psychology, Schenkman, 1963.

marginal ref. 51 — See Chapanis, Garner and Morgan, Applied experimental psychology, Chapman & Hall, 1949.

marginal ref. 52 — See pp. 102-4, P.H. Nowell-Smith, Ethics, Penguin, 1959.

marginal ref. 53 — This is also argued by P.H. Nowell-Smith, Ethics, Penguin, 1959, pp. 160-70.

marginal ref. 54 — Although work such as R.H. Brand's Measurement of fabric aesthetics, Textile Research Journal, vol. 34, no. 9, September 1964, is increasingly being undertaken.

marginal ref. 55 — See Miller and Starr in Executive decisions and operations research, Prentice Hall, 1960.

marginal ref. 56 — The term 'deterministic' and 'probabilistic' are derived from Stafford Beer, Cybernetics and management, English Universities Press, 1959. The term 'capricious' in this context is coined.

marginal ref. 57 — See Colin Cherry, On human communications, Chapman and Hall, 1957.

marginal ref. 58 — See Colin Cherry, On human communications, Chapman and Hall, 1957.

marginal ref. 59 — See Merrett and Sykes, The finance and analysis of capital projects, Longman, 1963.

marginal ref. 60 — This is only strictly true where the properties are independent variables. Both Russell L. Ackoff, Scientific method: optimising applied research decisions, Wiley, 1962, and Horst Rittel, 'Hierarchy or team?', Economics of research and development, Richard A. Tybout (editor), Ohio State University Press, 1965, examine the cases of dependent probabilistic variables and offer formulae for determining overall probability, but in slightly different contexts.

marginal ref. 61

This suggestion is made by W.I. Beveridge *The art of scientific investigation*, Heineman, 1957, in the course of comparing heuristic and scientific methods.

marginal ref. 62

Non-mathematicians are often greatly put off by paramathematical notation. Any reader who shares this feeling is invited to try the trick of reading out in the mind's ear the full verbal equivalent of each cipher, thus: "The degree (y) of satisfaction of objective O is some function of the state (x) of property P".

marginal ref. 63

See also *Executive decisions and operations research* by David W. Miller and Martin K. Starr, Prentice Hall, 1960.

marginal ref. 64

Often, the nature of a property is such that the concept "total lack of fulfilment of the objective" is unreal. In any case, the decision maker is not normally very interested in the precise evaluation of degrees of fulfilment of objective much below the threshold of acceptability (that is, where $O(y)$ is much below $\cdot 5$). In practice, therefore the identification of a real world value for, or state of, $P(v)$ can usually be dispensed with.

marginal ref. 65

"Arctan" means "the angle whose tangent is ......". To evaluate $O(y)$ the value for $[P(x)-P(1)]$ must be calculated from the given states $P(x)$ and $P(1)$ and this value looked up in a table of tangents of angles. From this table the equivalent degrees of angle must be identified and this number inserted in the numerator of the formula in place of the expression "arctan $[P(x)-P(1)]$". Of course the concept of an angle in the geometrical sense is irrelevant here, the arctan occurring simply as a convenient device for providing the right pattern of values.

marginal ref. 66

Either formulation may be used, according to which side of $P(u)$ the state $P(x)$ happens to lie in the case in question.

marginal ref. 67

Most designers tend to regard the solution of a problem by an act of invention as being more 'respectable' than solution by an act of negotiation.

marginal ref. 68 Russell L. Ackoff and C. West Churchman, in separate chapters of Progress in operations research: Vol. 1 Russell L. Ackoff (editor), Wiley, 1961, use similar definitions and notation.

marginal ref. 69 The relationship between a real world system, a logical model of the structure of that system, and an analogue used to imitate the behaviour of the system, is examined on p. 372 of Russell L. Ackoff's Scientific method: optimising applied research decisions, Wiley, 1962, (see also para. 3.15).

marginal ref. 70 The 'black box' idea is well described in A guide to operational research, Eric Duckworth, Methuen, 1962.

marginal ref. 71 From observation.

marginal ref. 72 See the preface to R. Schlaifer's Probability and statistics for business decisions, McGraw Hill, 1959.

marginal ref. 75 The term 'performance specification' (or P-spec) is used in a similar sense by J. Christopher Jones. See 'A method of systematic design' in Conference on design methods, J. Christopher Jones (editor), Pergamon, 1963.

marginal ref. 76 A similar reference to the concept of the decision resource occurs on p. 43 of Interdependence and uncertainty: digest of a report from the Tavistock Institute, Tavistock publications, 1966.

marginal ref. 77 S.S. Stevens, in On the theory of scales of measurement, Science 1946, 103, 677-80, recognises ratio scales (having a non-arbitrary zero and a constant unit of measurement), interval scales (having an arbitrary origin and a unit assumed to be constant), ordinal scales (having an order but no unit of measurement) and nominal scales (having identities by neither order nor measurement). See also Clyde H. Coombs in Psychological scaling without a unit of measurement, Psychological Review, vol. 57, May 1950, 3, 145-58.

marginal ref. 78 The term 'set', as used here, and the notation which follows are in accordance with the conventions of the theory of sets. See Irving Adler's The NEW mathematics, John Day, 1958.

marginal ref. 79

Techniques for ranking and testing the validity of rankings are well described in M.J. Moroney's Facts from figures, Penguin, 1951.

marginal ref. 80

W.I. Beveridge in The art of scientific investigation, Heineman, 1957, draws a nice distinction between the heuristic disciplines of the manager, designer and technologist, which are directed towards getting answers which work, whether the reasons are understood or not, and the classical discipline of the scientist, which is directed towards finding proofs for hypotheses, no matter how limited or useless (in the 'pure' science sense) these may appear to be.

marginal ref. 81

The book Economics of research and development, edited by Richard A. Tybout, Ohio State University Press, 1965, contains a collection of histories and theoretical papers, many of which relate to these aspects of the design function.

marginal ref. 82

The presentation of business activities in this sort of problem solving format can be seen in A.M. McDonough's Information economics and management systems, McGraw Hill, 1963.

marginal ref. 83

F. de P. Hanika in New thinking in management, Hutchinson, 1965, describes management problems generally as examples of programmed problem solving.

marginal ref. 84

That all decisions are based upon some implicit or explicit assessment of the probability and consequences of the alternative outcomes, based upon some system of values, is the basic premise of R. Schlaifer's Probability and statistics for business decisions, McGraw Hill, 1959.

marginal ref. 85

This mechanism is made explicit by W.J. Fabrycky and Jerry Banks in Procurement and inventory systems: theory and analysis, Reinhold, 1967.

marginal ref. 86

Economists tend to use the term 'utility' for any property which gives an artefact value in human eyes, again see W.J. Fabrycky and Jerry Banks, Procurement and inventory systems: theory and analysis, Reinhold, 1967.

marginal ref. 87	This formulation is based mainly upon the examination of the case studies listed in the appendix. It is substantially in accordance with similar patterns observed by Morris Asimow, Hugh M. Bowen, J. Christopher Jones, R.L. Latham, R.J. McRory, E. Matchett, Horst Rittel and Martin K. Starr (see bibliography 4).
marginal ref. 87A	Fig. 6.11 represents the essence of the findings of this thesis, explicitly summarised in Section 11.
marginal ref. 88	F. de P. Hanika gives a number of examples in New thinking in management, Hutchinson, 1965. See also Greene and Sisson, Dynamic management and decision games, Wiley, 1959, and S. Vajda's An introduction to linear programming and the theory of games, Methuen, 1960.
marginal ref. 90	Under some circumstances, a rise in price in response to scarcity is prevented, for example by governmental price controls. Sometimes the inconvenience of queueing or other non-cash premiums replace the price mechanism. In any case, the tendency to a rise in price accompanies scarcity.

marginal ref. 91 — In a manual, setting out a scale for measuring human values (Study of values, Houghton Mifflin, 1960), Gordon W. Allport, Philip E. Vernon and Gardner Lindzey employ six classes of motives: theoretical, economic, aesthetic, social, political, religious. The subdivisions of some of these coincide roughly with the factors given here.

marginal ref. 92 — E.J. McCormick's Human Engineering, McGraw Hill, 1957, provides a convenient and fairly comprehensive definition and review of ergonomics.

marginal ref. 93 — Both Russell L. Ackoff in On a science of ethics, Philosophy and Phenomenological Research, Vol. IX (1949), pp. 663-72, and C. West Churchman in Prediction and optimal decision, Prentice Hall, 1961, regard all judgements in science, business, aesthetics or anything else as falling within some ethical system.

marginal ref. 94 — For example, see R.H. Brand's description in Measurement of fabric aesthetics, Textile Research Journal, Vol. 34, No. 9, September 1964, of an enquiry identifying the components of people's aesthetic reactions to textiles, measuring them by means of the semantic differential developed by Osgood, Tannenbaum and Suci in The measurement of meaning, University of Illinois Press, 1957.

marginal ref. 95 — E.H. Gombrich argues this very lucidly in Art and illusion, Phaidon, 1956.

marginal ref. 96 — The existence and nature of uncertainty in the design and construction of buildings is argued from case studies in Interdependence and uncertainty: digest of a report from the Tavistock Institute, Tavistock Publications, 1966.

marginal ref. 97 — See Martin K. Starr, Product design and decision theory, Prentice Hall, 1963.

marginal ref. 98 — I.J. Good, Rational decisions, Journal of the Royal Statistical Society, B, Vol. 14, 1952, identifies the overall goal of a project as the maximisation of expected utility, where:

Expected utility = (Probability x value of success) − (Probability x cost of failure)

marginal ref. 99	The National Economic Development Council examines this relationship in Investment appraisal, Her Majesty's Stationery Office, 1967.
marginal ref. 100	This is a modification of the expected utility formulation described by Good.
marginal ref. 101	R. Schlaifer, Probability and statistics for business decisions, McGraw Hill, 1959, argues that the choice of a course of action should be based upon the value of the consequences and the probability that they will occur.
marginal ref. 102	See Miller and Starr, Executive decisions and operations research, Prentice Hall, 1960. Miller and Starr also offer criteria for the selection of courses of action in the face of uncertainty, including the Laplace criterion ("if we know of no reason for the probabilities being different, regard them as being the same").
marginal ref. 103	See Computers and production control, Institution of Production Engineers, 1961.
marginal ref. 104	This is more or less the overall tenor of C. West Churchman's Prediction and optimal decision, Prentice Hall, 1961.
marginal ref. 105	Both Stafford Beer, for example in Cybernetics and management, English Universities Press, 1959, and Gordon Pask, for example in An approach to cybernetics, Hutchinson, 1961, have outlined the principles for self-organising systems incorporating automatic hypothesis-generating features.
marginal ref. 106	Some studies of the basis of human creativity carried out at the Institute of Personality Assessment and Research, University of California, and at Pennsylvania State University, are quoted in Hydrocarbon Processing and Petroleum Refiner, vol. 41, no. 10, October 1962, pp. 110-111.

marginal ref. 107

Several such mixed techniques have been proposed, for example J. Christopher Jones, 'A method of systematic design', Conference on Design methods, J. Christopher Jones (editor), Pergammon, 1963, and E. Matchett, The Controlled evolution of engineering design, Engineering Designer, February 1965. See also the University of Chicago Manual on brainstorming and Massachusetts Institute of Technology List of idea-spurring questions, both published by the Creative Education Foundation, Buffalo, New York.

Postscript

The designer of this book, Brian Grimbly, has known the author for a number of years. Whilst art editor of DESIGN magazine he prepared many of the author's articles for print. Their co-operation has always been a two-way process, and wherever possible the typographic aspects of communication have been allowed to play a role ab initio in the shaping of the argument. It seemed appropriate to continue this co-operation in the present case, and to use the task of designing the book as a worked example of the ideas presented in the text.

The following is therefore a record, using the notation set out in the body of the book, of Mr. Grimbly's train of reasoning in arriving at his design. For a test of the adequacy of that reasoning, the reader should look back at the book itself: