Design Research Society

DRS Digital Library

Materials Relating to the 1962 Design Methods Conference

DRS Archive

1963

Conference on Design Methods

J. Christopher Jones
Manchester College of Science and Technology

D. G. Thornley
University of Manchester

Follow this and additional works at: https://dl.designresearchsociety.org/design_methods_conference_1962

 Part of the Architecture Commons, and the Art and Design Commons

Citation

Jones, J., and Thornley, D. (eds.) (1963) *Conference on Design Methods*
https://dl.designresearchsociety.org/design_methods_conference_1962/1

This Book is brought to you for free and open access by the DRS Archive at DRS Digital Library. It has been accepted for inclusion in Materials Relating to the 1962 Design Methods Conference by an authorized administrator of DRS Digital Library. For more information, please contact dl@designresearchsociety.org.

PERGAMON PRESS LTD.
Headington Hill Hall, Oxford
4 & 5 Fitzroy Square, London, W.1

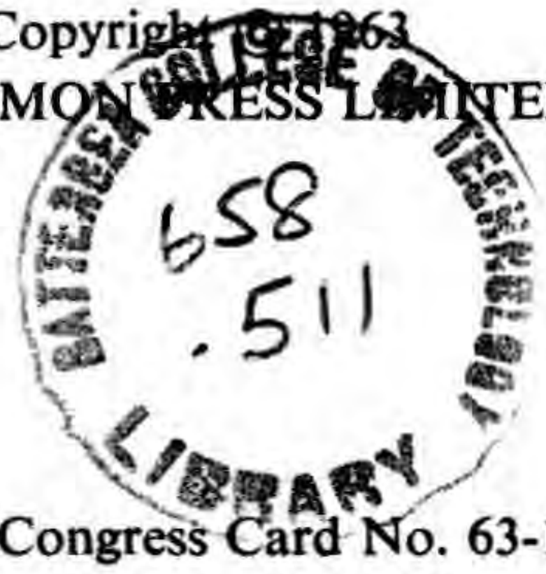
PERGAMON PRESS INC.
122 East 55th Street, New York 22, N.Y.

GAUTHIER-VILLARS ED.
55 Quai des Grands-Augustins, Paris 6

PERGAMON PRESS G.m.b.H.
Kaiserstrasse 75, Frankfurt am Main

Distributed in the Western Hemisphere by
THE MACMILLAN COMPANY · NEW YORK
pursuant to a special arrangement with
PERGAMON PRESS INC.
New York 11, N.Y.

Copyright © 1963
PERGAMON PRESS LIMITED



Library of Congress Card No. 63-18671

Set in 10 on 12 Times Roman by Santype Limited, Salisbury,
and Printed in Great Britain by Barnicotts Ltd Taunton
Cover Design and Titling by
Leslie Saxon, Regional College of Art, Manchester

J. CHRISTOPHER JONES

A Method of Systematic Design

INTRODUCTION

A trend towards more logical and systematic methods of design has been evident throughout the 1950's. In many cases they have appeared as the result of new technical developments such as computers, automatic controls and systems. During the same period there have been attempts to give more scope for imagination and creative thought in design under such titles as "creative engineering" and "brainstorming".

The following notes are an attempt to integrate all such developments as have come to the writer's notice into a unified system of design. It is aimed particularly at the area that lies between traditional methods, based on intuition and experience, on the one hand, and a rigorous mathematical or logical treatment, on the other. The method is intended to have two effects:

1. To reduce the amount of design error, re-design and delay.
2. To make possible more imaginative and advanced designs.

It is thought that the method can be usefully applied to design problems in any area in which:

1. Large quantities of design information are available, or can be usefully obtained.
2. The design team has well-defined responsibilities, can concentrate on development, and is free of routine design work.
3. Considerable departures from existing designs are called for.

Some parts of the suggested method (Sections 1.1, 1.2, 1.3, 1.4, 1.5, 2.2, 2.3, 2.4) have been tried out with some success in design teaching projects and in prototype development in ergonomics and industrial design. In these cases it has seldom been possible to carry the method through to a logical conclusion for want of the new kind of design organization that seems to be necessary to permit a complete change to systematic work. Other parts of the method are based more on conjecture, and on the reports of others, than on the writer's experience. In many cases the suggested methods are better regarded as a basis for further investigation than for application in current design work.

Opportunities to try out some of the ideas presented here have been

provided by the Industrial Design Office at Associated Electrical Industries, Manchester, and by the Regional College of Art, Manchester. For the patience with which those concerned in both these organizations have awaited, and still await, a substantial result from these activities, the writer is very grateful. Perhaps this conference will mark the beginning of a phase when systematic design methods will develop more rapidly towards the degree of reliability and realism that is necessary before they can be generally applied.

SUMMARY

The method is primarily a means of resolving a conflict that exists between logical analysis and creative thought. The difficulty is that the imagination does not work well unless it is free to alternate between all aspects of the problem, in any order, and at any time, whereas logical analysis breaks down if there is the least departure from a systematic step-by-step sequence. It follows that any design method must permit both kinds of thought to proceed together if any progress is to be made. Existing methods depend largely on keeping logic and imagination, problem and solution, apart only by an effort of will, and their failures can largely be ascribed to the difficulty of keeping both these processes going separately in the mind of one person. Systematic Design is primarily a means of keeping logic and imagination separate by external rather than internal means. The method is:

1. To leave the mind free to produce ideas, solutions, hunches, guesswork, at any time without being inhibited by practical limitations and without confusing the processes of analysis.
2. To provide a system of notation which records *every* item of design information outside the memory, keeps design requirements and solutions completely separate from each other, and provides a systematic means of relating solutions to requirements with the least possible compromise. This means that while the mind moves from problem analysis to solution-seeking whenever it feels the need, the recording develops in three distinct stages:
   1. Analysis
      Listing of all design requirements and the reduction of these to a complete set of logically related performance specifications.
   2. Synthesis
      Finding possible solutions for each individual performance specification and building up complete designs from these with least possible compromise.
   3. Evaluation
      Evaluating the accuracy with which alternative designs fulfil performance requirements for operation, manufacture and sales *before* the final design is selected.

All the stages of SYSTEMATIC DESIGN are listed below. Details of each stage appear on the succeeding pages.

1. Analysis	1.1. Random list of factors
	1.2. Classification of factors
	1.3. Sources of information
	1.4. Interactions between factors
	1.5. Performance specifications
	1.6. Obtaining agreement
2. Synthesis	2.1. Creative thinking
	2.2. Partial solutions
	2.3. Limits
	2.4. Combined solutions
	2.5. Solution plotting
3. Evaluation	3.1. Methods of evaluation
	3.2. Evaluation for operation
	for manufacture
	for sales

1. ANALYSIS

1.1. *Random List of Factors*

At the first meeting each person writes a list of all the thoughts that occur to him on acquaintance with the problem. Each person reads out his list and all items are recorded in serial order in a RANDOM LIST OF FACTORS. No attempt is made to avoid duplication or to omit impractical ideas. In the ensuing discussion there is a complete ban on criticism or comment on the ideas produced. The object is to get down a large amount of information in a short time in an atmosphere in which all feel assured that no idea will be inhibited or ridiculed.

The discussion can include, or be followed by, a similar random list of criticisms made while looking at examples, drawings and reports of the existing designs and at the ideas and information collected above.

Once the initial reactions and feelings about the problems have been recorded, the random list should be extended until it includes every single factor which could be thought to influence the design. This is to include all the obvious factors which may not have been mentioned in the initial discussion.

The notation for a RANDOM FACTORS LIST is to number each factor in the order in which they are first considered, e.g. some of the factors for the redesign of an electric motor might be numbered as follows:

1. Improve output per unit volume,
2. Access to terminals,
3. Fit existing couplings,

4. Overall height—reduce,
5. Heat dissipation—method using less volume—faster coolant speeds,
6. Existing design clumsy looking,
7. Why waste so much energy as heat—what would reduce the losses? List all possible items later,
8. Shaft diameter, shaft length, keying method,
9. Method of slinging,
10. Can use of crane be avoided?
11. Possible new materials, etc., up to a very large number of items, perhaps several hundred.

1.2. *Classification of Factors*

At this stage, and at any later stages when the information may be too disorderly to reveal any general pattern, a CLASSIFICATION CHART can be used to find the alternative categories into which the factors fall:

Factors	Categories					
	1	2	3	4	5	etc.
1.	×					
2.		×				
3.			×			
4.		×				
5.				×		
6.	×		×			
etc.						

The random factors are placed in categories by choosing a category title (category 1) for the first factor (factor 1), then choosing another category for factor 2, another for factor 3, etc., and denoting categories by crosses as shown. Factors may fall into categories already noted, e.g. factor 4 in category 2, or into more than one category, e.g. factor 6 in categories 1 and 3.

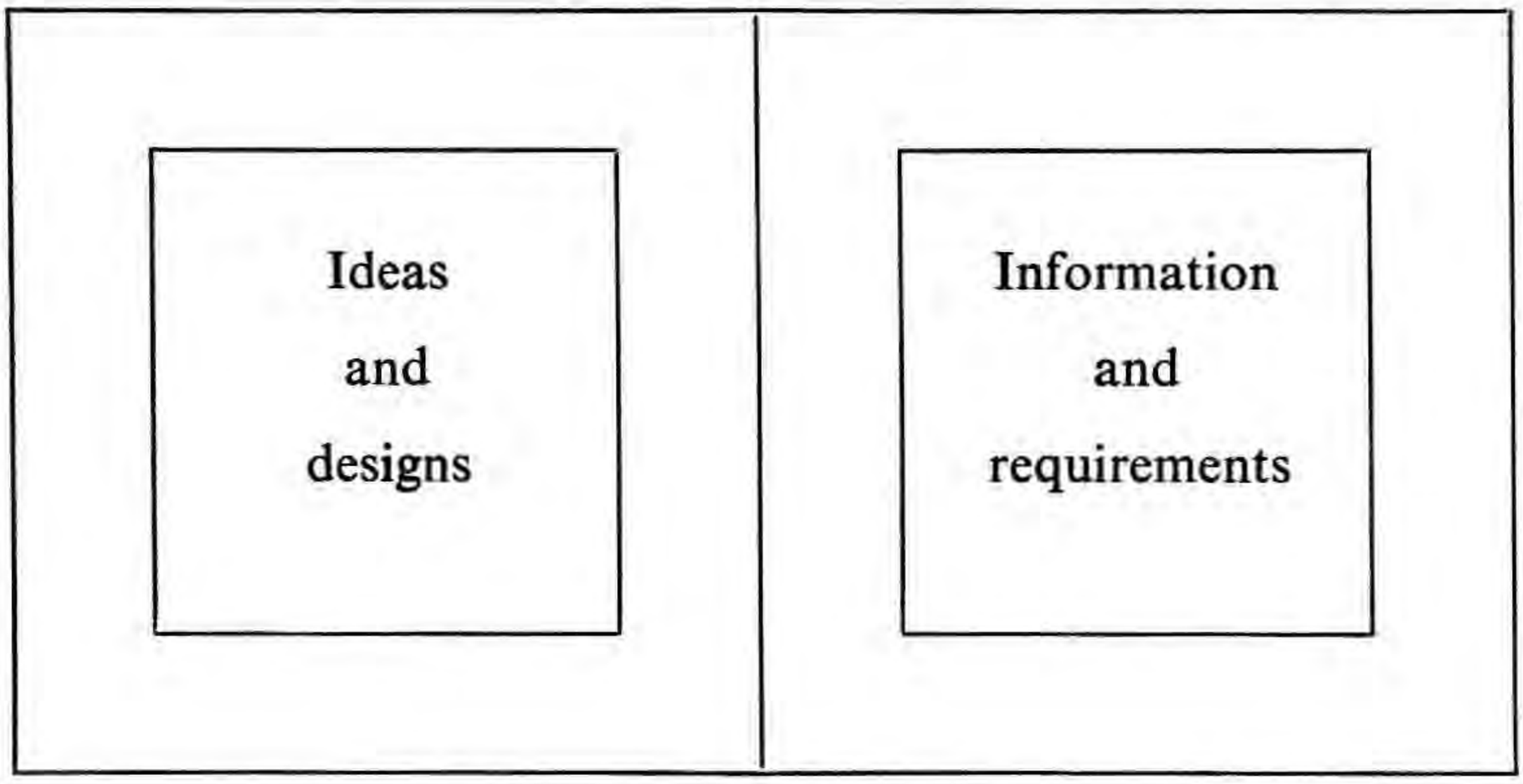
The factors are then copied out on separate sheets for each category:

Category 1	
1	
6	
15	
etc.	

using the same factor numbers. It may be necessary to make another classification chart to find the sub-divisions of categories containing many factors.

Usually the act of writing out the factors in separate categories suggests further additions and begins to show up areas where more information is required.

One special category will be "ideas, solutions, design proposals, etc.". These should be copied on to a separate sheet to which many more ideas will be added as the work proceeds. Ideas sheets should be kept completely separate from information and design requirement sheets—possibly on the opposite sides of a folder:



An alternative method is to write each factor on a separate index card and to sort these into alternative sets of categories and sub-categories until an acceptable arrangement is found.

1.3. *Sources of Information*

The previous steps will have produced, from the existing knowledge of the design team, a very large quantity of information, much of it conflicting and in need of verification. Classification will have suggested further factors, will show up areas where further information is needed and will also suggest

likely sources, e.g. the category "Maintenance" might show up ignorance of what the maintenance difficulties are and suggest consultation with, and observation of, maintenance staff. In any category the possible sources of information are literature, experienced persons, observations and experiment.

Literature. Technical and trade journals, abstracts, research reports, technical libraries, etc., contain nearly all that is known about any existing problem. But the location of information relevant to one's own particular problem can be so time-consuming and expensive that it often seems more helpful to rely on one's own judgement or to make a new investigation oneself despite the risk of missing important technical developments and despite the additional cost of investigations which may already have been carried out, and paid for, by others. Some of the very real difficulties of using literature in design can be overcome in the following ways.

Use of libraries and information services. Technical libraries report that enquirers have difficulty in explaining their needs in a way which would make it possible for library staff to help them. Most people describe their interests too broadly, for fear that the librarian will miss something important, and so they get back a large quantity of material that is irrelevant or already familiar. The correct method is to tell the librarian not what you know but *what it is you do not know* as precisely as possible, e.g. instead of asking for "any information on the cooling of electric motors?" describe what it is you do not know in such terms as "what are the costs and efficiencies of the various methods of heat transfer that have been applied to electric motors?"

The extraction of relevant information. The quantity of technical literature is so great that one cannot hope to remember or collect much useful information from general reading until one has a particular problem in mind and by then there often seems to be no time available for such time-consuming browsing. One answer is to do a relatively small amount of intensive reading of a few publications while the random factors list is being compiled and note down all factors that are suggested by what is read. It is astonishing how much useful information, that one would normally have missed, comes to light when one has so definite a purpose in reading. This process can be usefully continued until factors begin to repeat themselves and new factors cease to be found very often.

Experienced persons. Vast quantities of valuable and highly relevant design information exists in the memories of persons experienced in design, manufacture, operation, costing, sales, maintenance, installation, transport, etc. It is often not made use of because the facts are so mixed up with personal opinions and because it is so difficult to explain one's experience to someone else. However it is worth trying the following methods of overcoming these difficulties.

Separating opinion from fact. The obvious way to do this is to ask each question of two or more people and treat as opinion all those items on which

they disagree. Items on which they agree are then either facts, or opinions which are widely held. It may be possible to sift out the latter by some objective checks and measurements. When there is no means of checking, and when experienced persons are the only available source, it is important to act only on the advice of persons who will afterwards be *held responsible* for what they recommend. Opinions of any other persons, whatever their status or authority, cannot be incorporated into a design unless they are shared by a person who is to be held responsible for their effect upon the design.

Judgement between limits. Experienced people are often reluctant to commit themselves to precise answers and instead give very general answers that are of little help in design. The answer here is to press for judgement between precise limits, e.g. an experienced costing engineer may be reluctant to quote any figure on the basis of a rough sketch but if asked to state the *limits of his uncertainty* will be able to give a maximum and minimum cost which will be a far more accurate guide than any guess which questioner could make. Almost any experience can be expressed between limits if the question is properly stated in terms of the quantity which will affect the design itself.

Logical question chains. Although opinions may be useless in themselves they are often based on factual experience which can be extracted by a chain of logically related questions, e.g.

Opinion : Customers will not consider electronic controls under any circumstances.
Question : Why will they not consider them?
Answer : Because they are unreliable.
Question : In what way are they unreliable?
Answer : They are always going out of order.
Question : But do not existing kinds of controls go out of order?
Answer : Yes, but you have time to do something about it before the thing packs up completely.
Question : Electronic controls give no warning of failure then?
Answer : Yes—I suppose that is it—an electronic control that gave a warning would be acceptable.

The logical question chain has tracked down the basic fact which caused the opinion and which shows up a possible method of overcoming what seemed at first like an irrational opinion that prevented all progress in design.

Observation. The difficulty of observation is that in any practical situation there is so much to see that one cannot select the facts that are relevant to one's own problem. Some methods of overcoming this difficulty are:

Recording for Analysis Later

The obvious way to overcome the difficulty is to do the selecting of relevant facts at a later time and in a less distracting environment. Two methods of recording can be used.

1. *Unabstracted recording* such as photographs, films and general notes which record all that can be seen and leave a great choice of facts from which to select for analysis. Such methods can record significant information that was not expected beforehand but involve lengthy and costly analysis and do not give very definite answers.
2. *Abstracted recording* such as pen recorders, punched tape, checking facts on prepared forms. Such methods omit everything that was not expected beforehand but greatly reduce the time and cost of analysis and give very definite answers.

It is clear that initial observations should be of type 1 and that later observations should be of type 2.

Experiment. It is sometimes necessary to resolve a doubtful point by direct experiments or trials. As in the above cases of observation the important things are to:

1. State clearly what one does *not* know and within what limits.
2. Calculate or estimate the limits of errors in the experimental situation.
3. Before designing the experiment decide what actions will be taken for each of the possible outcomes.

This procedure gives the greatest amount of useful information for the least expenditure of time and effort.

1.4. *Interactions between Factors*

Many factors affecting design interact with one another to make up a complicated situation which can be appreciated by experience. The systematic approach is to use charts, to ensure that all possible interactions are discovered, and diagrams, to make clear the pattern of relationships.

There are many mathematical and diagrammatic methods of doing these things. Two very elementary methods which have very wide applications in the finding of relationships in randomly assembled information are given here.

All possible combinations, by pairs, of the factors 1, 2, 3 etc. appear in the squares to the right of the diagonal line of the interaction matrix. Each pair is considered separately and when an interaction is found it is denoted by a cross. Examples of the use of this chart are:

1. Discovering all factors influencing an existing design by listing all the parts of the design, and all the elements with which it has contact, as factors. For every pair of factors which is found to interact there will be a requirement which can afterwards be expressed as a performance specification (see Section 1.5). This procedure is particularly useful when one or two design requirements have changed and it is necessary to find out how these changes will affect the rest of the design. Such a check will sometimes make it clear that the whole problem has also changed and an entirely new design is called for.

Interaction matrix:

Factors	1	2	3	4	5	6	7	8	9	...
1				+				+		
2			+			+			+	
3							+		+	
4					+			+		
5									+	
6										
7									+	
8										
9										

2. When the design problem involves the linking of many elements as in the case of circuits, pipework, building layouts, communication systems. The required linkages can be checked by listing all the parts of the system as factors and deciding whether or not a link is required on every possible interaction.

Interaction matrices can also be used to establish sequences and orders of importance of factors. In this case the whole area of the chart is used.

Factors	1	2	3	4	5	6		
1 C		+	+			+		
2 F								
3 D		+				+		
4 A	+	+	+		+	+		
5 B	+	+	+			+		
6 E		+						
Totals	2	5	3	0	1	4		

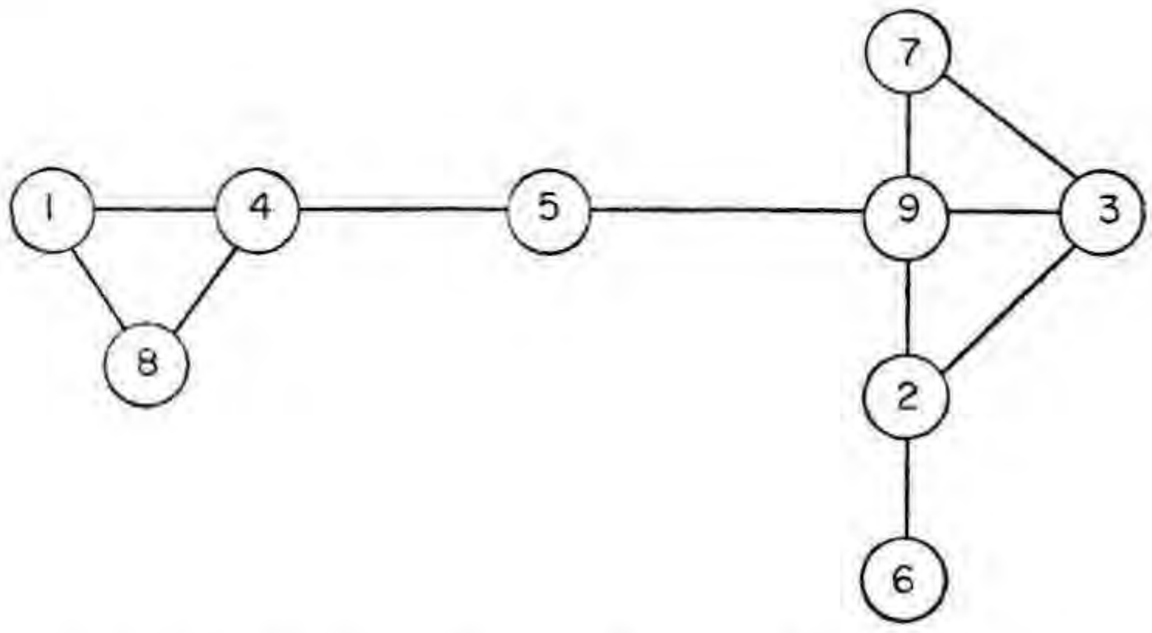
Each cross denotes that the factor in the rows across comes before the corresponding factor in the column, e.g. the cross at square 1–2 means that factor 1 comes before (or is more important than, or has some kind of sequential effect on) factor 2. The totals give the final sequence of factors 1–6 namely:

Total	0	1	2	3	4	5
Factor	A	B	C	D	E	F

This method of establishing sequences can be applied to such things as:

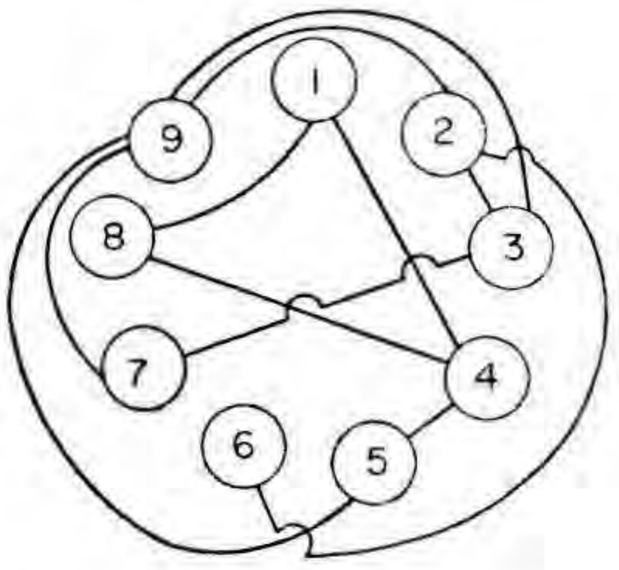
1. Finding the operating sequence for a number of controls. In this case each cross indicates that the control in the row affects the operation of the control in the column but not vice versa.
2. Placing a number of design requirements in order of importance. This is a good method for weighting factors prior to decision making.

Interaction nets. The pattern of relationships between a number of interacting factors can be made easy to see by replotting the information from a matrix as a net.



Each number refers to a factor and each line refers to a cross in the interaction matrix. The above interaction net is obtained in two stages.

1. Write out the numbers in a circle and draw in the links, corresponding to the crosses, with as few crossed lines as possible—starting with numbers which have many links.



2. Re-draw in an orderly way keeping groups of interconnected numbers apart from each other and with as few crossed lines as possible, as in the first diagram above. In very complicated cases confusion can only be avoided by the use of a three-dimensional model.

Examples of the use of interaction nets are:

1. Making clear the pattern of interactions between all the performance specifications in a problem and thus giving an idea of the consequence of changing any particular requirement.
2. Making clear the pattern of linkages in any problem that involves the interconnection of many parts, e.g. circuits, systems, circulation plans.

1.5. *Performance Specifications* (P-SPECS)

Complete separation of problem from solution can only be achieved if the requirements are expressed purely in terms of performance and with no reference whatever to shape, materials and design. To do this each requirement is rewritten as a PERFORMANCE SPECIFICATION (or P-SPEC), e.g.:

Design specification:

Control panel to be mounted at 45°

P-SPEC:

Control panel to be visible from all operating positions.

It is often difficult for those who are accustomed to working by experience rather than analysis to think in terms of performance by itself. This difficulty can often be overcome by subjecting each requirement to a LOGICAL QUESTION CHAIN (see Section 1.3.).

P-SPECS should be expressed wherever possible between LIMITS (as in Section 1.3), e.g.

P-SPECS between limits:

Control panels to be visible within $\pm 20°$ of the normal from all positions of the eyes for persons of height between 5 ft 3 in. and 6 ft 2 in.

Heat dissipation to be between 10 and 20 per cent more than for existing design.

In all cases the limits should be as far *apart* as is in keeping with the standards of performance aimed at.

1.6. *Obtaining Agreement*

The complete list of P-SPECS is circulated to all persons whose agreement to the final design will be required at a later stage. At subsequent meetings and discussions every effort is made to incorporate all valid criticisms and omissions in a revised list. Written agreement of all concerned is sought at this point on the strict understanding that the design will go ahead on this basis and all further alterations or additions will have to be held over for incorporation in future designs.

The strict finalizing of the P-SPEC list will only be possible when the preliminary work has been very thorough. When this degree of thoroughness has not been achieved, major errors and omissions in the P-SPECS are likely to be discovered at later stages. In these cases it will not be possible to maintain separation of problem and solution and SYSTEMATIC DESIGN will have ceased

to occur. This failure is likely to occur when SYSTEMATIC DESIGN is tried out for the first time in situations where traditional methods are customary. The great difficulty of introducing SYSTEMATIC DESIGN is that its advantages are not obtained unless it is carried out far more thoroughly than is likely in first attempts. Successful application is much more likely when changes in ORGANIZATION have been introduced beforehand. As with many new things it involves an acclimatization period during which things may get worse before they get better.

2. SYNTHESIS

2.1. *Creative Thinking*

Little is known of what goes on in the mind during creative thinking, but it is clear that the power of imagination which any person can apply to the solving of a design problem is dependant on two external factors:

1. A clear statement of the problem.
2. A free atmosphere in which any idea, however crude or naïve, can be expressed at any time without regard to its practicability. The purpose of all the previous stages is to make possible a very clear statement of the problem. This work will in itself suggest many ideas and solutions which will have been collected in a separate set of papers as described in Section 1.2. When the P-SPECS have been completed a much more deliberate search for solutions can begin.

A useful technique is that described as BRAINSTORMING. Those concerned with the project, and a number of other persons of different backgrounds and experience, are invited to an informal meeting. After each item of the performance specification is read out all persons are asked to mention any idea, criticism or solution that comes into their heads however mad or eccentric it may appear to be. The chairman does nothing except read out the problems and enforce the rule that nobody shall criticize any idea in any way. All ideas are recorded in shorthand or by tape recorder for evaluation later.

The same method of uninhibited listing of ideas can be done by individuals. This procedure is valuable as a means of releasing the imagination and of obtaining a large number of ideas from many areas of experience in a short time. It should be followed by more logical and careful thought, particularly on those aspects of the problem where no obvious solutions have appeared so far. In such cases, if the imagination comes to a halt and no solution seems possible the following methods may suggest a solution:

1. Write down the conditions which would make a solution possible.
2. Write down a phrase describing the difficulty and substitute alternatives for each word, e.g.

PHRASE DESCRIBING A DIFFICULTY

"Manufacturing tolerances will cause misalignment between two surfaces."

ALTERNATIVE WORDS

Substitute "welding distortion" for "manufacturing tolerances":
This suggests using a process other than welding.
Substitute "a gap between" for "misalignment":
This suggests making a deliberate gap.
Substitute "adjacent surface" for "two surfaces":
This suggests making the surfaces not adjacent, i.e. putting another surface between them.
Substitute "planes" for "surfaces":
This suggests making the surfaces non-planar.

3. Write down the consequences of not finding a solution of the difficulty. This will often show that the consequences can in fact be tolerated, or suggest another way of avoiding them.

2.2. *Partial Solutions*

Existing design methods usually result in a single solution which is conceived as a whole with the details being worked out later. SYSTEMATIC DESIGN reverses this procedure. PARTIAL SOLUTIONS, one or more for each P-SPEC, are sought first and then combined by permutation to give several alternative whole solutions.

Partial solutions to each of the P-SPECS are tabulated as follows:

P-Specs	Partial Solutions
1	
2	
3	

A vital difference between this and existing methods is that each PARTIAL SOLUTION is considered *completely independently* of any other. The object is to find shapes which meet each P-SPEC in the best possible way and to take no account of conflicting demands of different P-SPECS, e.g. if one P-SPEC is best satisfied by a removable access cover and another is best satisfied by a fixed enclosure these best solutions should be separately recorded, together with some estimate of the degree of performance loss for departures from complete accessibility and complete enclosure respectively. This makes it possible to find COMBINED SOLUTIONS having the *least compromise* at stage 2.4.

Sources of Partial Solutions are:

1. A search through the ideas collected so far.
2. The use of BRAINSTORMING, and the other more logical methods described in Section 2.1 as aids to creative thinking.

3. Observation and experiments with existing designs and experimental apparatus to measure the degree to which any particular P-SPEC is satisfied, without reference to any other.

All solutions should be expressed in terms of physical dimensions between limits as described in the next section.

2.3. *Limits*

There will be a *range* of dimensions, shapes, and variations in material properties, which will satisfy any particular P-SPEC. It is vital to express PARTIAL SOLUTIONS by LIMITS which show clearly the extremes between which all such equally acceptable solutions lie. This means that:

1. All dimensions, radii, etc., to be followed by the widest acceptable tolerance, e.g.:
   $+1$ in. $-$ 1 in., $+1$ in. $-$ 0 in., $+0$ in. $-$ 1 in.
2. All shapes to be expressed as a range of shapes, e.g. any shape lying between a square and a circle.
3. Choice of materials to be expressed between limits of their properties, e.g. any materials have $A \pm a$ hardness, $B \pm b$ elasticity, etc.

2.4. *Combined Solutions*

The purpose of this stage is to combine PARTIAL SOLUTIONS into COMBINED SOLUTIONS with the least departure from the P-SPECS. This can be done to some extent by looking down the list of PARTIAL SOLUTIONS and selecting by eye those that appear to go best together. But as this process involves far more alternatives than the memory can handle without confusion it is necessary to do this in stages.

1. By inspection, and a little trial and error, make lists of
   (a) PARTIAL SOLUTIONS which are compatible, i.e. do *not* conflict.
   (b) PARTIAL SOLUTIONS which are incompatible, i.e. *do* conflict.
   An INTERACTION MATRIX (1.4) can be used to check the compatibility of each pair of solutions.
2. Look again at the INTERACTIONS BETWEEN FACTORS (1.4) to find logical sequences in which PARTIAL SOLUTIONS should be combined. For example, in the design of an automatic control system the INTERACTION NET might show that:
   (1) The *type of switching element* is dependent on:
   (2) The *frequency of switching*, which is dependent on:
   (3) The *speed of response*, which is dependent on:
   (4) The *acceptable error*, which is dependent on:
   (5) The *relative costs of errors* and *error-correcting devices*:

It is correct to begin with the most independent factor, in this case the cost of errors, and to combine PARTIAL SOLUTIONS in the sequence 4, 3, 2, 1, 5, repeating the process until the optimum for 5 is obtained. In this way sets

of compatible particular solutions, each following within the LIMITS of their respective PARTIAL SOLUTIONS, can be obtained.

Compatible PARTIAL SOLUTIONS can be tabulated as follows:

P—SPECS	Sets of compatible partial solutions					
	Set 1	Set 2	Set 3	Set 4	Set 5	
1	P11	P12	P13	P14		
2	P21	P22				
3	P31		P33			
4		P42	P43	P45		

P12 is a partial solution. The figure 1 indicates that it falls between the dimensional limits of the PARTIAL SOLUTIONS for P-SPEC No. 1. The figure 2 indicates that it is compatible with all the other solutions in set 2, compatibility having been discovered by both or either of the methods 1 and 2 above. It may be more convenient to put small illustrations on the chart in place of the symbols P12, etc., and so make it possible to see at a glance the *way* in which the particular solutions will fit in with each other.

As the gaps in the above chart indicate, no set of compatible solutions will meet all the P-SPECS. The problem then is to decide which combinations give least compromise and loss of performance. Often the only way to do this is to develop several sets to the stage where their performance can be evaluated by trial and experiment.

The design method described so far will still leave a great many detailed decisions to be made by eye and by experience.

2.5. *Solution Plotting*

Systematic design does not seek a single solution but aims at finding a range of solutions and making it clear in what ways each fits, or does not fit, the specification. Finally, when it becomes necessary to select one or more of these solutions for production, the selection can be made in full awareness of the results which can be expected, and with a high probability that no better solutions can be found with the existing resources.

Solution plotting is a means of making clear the relationships between solutions. Two kinds of relationship are considered here.

Trends—i.e. relationships between previous solutions.

New solutions—i.e. relationships between all possible alternative solutions.

A trend plot can be used to show how shape and performance have changed over the years. Photographs or drawings of previous designs are placed in

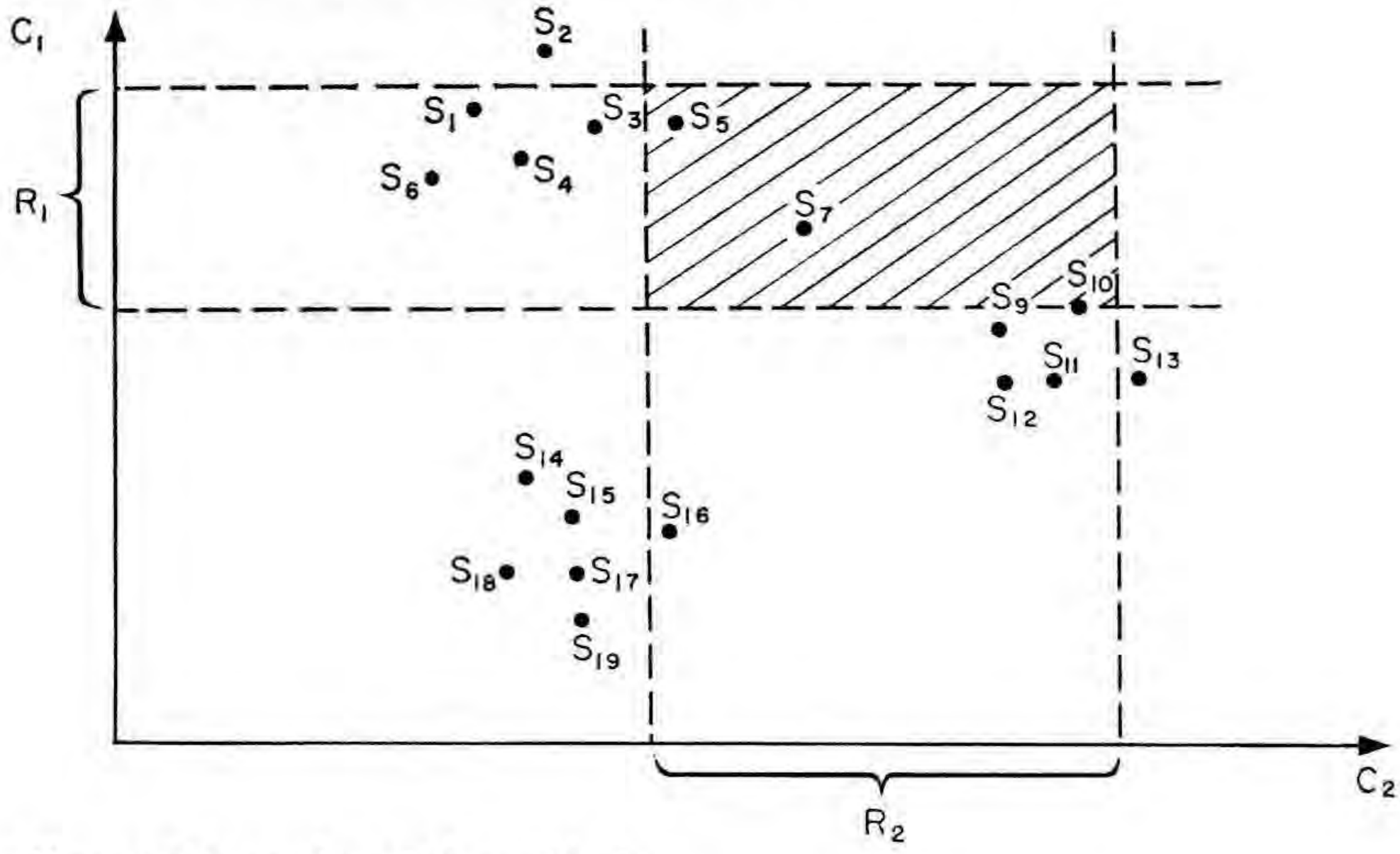
sequence and data are added in terms of reasons for design changes and details of performance achieved.

Trend plot

Year	Year 1	Year 2	Year 3	Year 4	Etc.
Illustrations	Original design	—	First design change	Second design change	—
Reasons for design changes	—	—	Reasons	Reasons	—
Performance for Factor 1	Performance	—	Performance	Performance	—
Performance for Factor 2	Performance	—	Performance	Performance	—
Etc.					

The gaps which occur in years where no design change takes place serve to illustrate the life of each design and are helpful in indicating the degree of design change that is appropriate at the present time.

A new solution plot is a means of comparing the range of existing solutions, or new proposals, in relation to shape or performance. These plots can be used to find areas where new combinations of shape and performance can be sought and will also show up areas where the existing solutions are likely to be the best. New solution plots for both shape and performance take the form of graphs in which measures of two major characteristics of shape or performance are marked along the axes. Each of the points S1, S2, etc., marks the characteristics C1 and C2 of solutions.



C1 and C2 can be of three kinds:

1. Two measures of *performance*, e.g. speed and reliability, cost and capacity.

2. Two measures of *shape*, e.g. weight and length, volume and type of material.
3. A measure of *performance* and a measure of *shape*, e.g. speed and weight, maintainability and degree of enclosure.

The measures used to quantify characteristics C1 and C2 are either existing scales, such as weight and cost, or ranks obtained from making estimates and judgements between every pair of solutions using an interaction matrix (Section 1.4) to rank them in sequence.

The results of plotting all the alternative existing solutions S1, S2, S3, etc., might be patterns such as that shown. In the above example one might conclude: that existing shapes and materials tend to three basic design types, represented by the three clusters; that the central designs in each cluster may be the best obtainable example of their types; that isolated examples, such as S7, may be hybrids which will move towards one of the neighbouring clusters if modified to increase either of the characteristics C1, C2.

When the ranges of desired characteristics, shown as R1, R2, are known, the area in which both occur can be marked on the solution plot. In this case the position of the shaded area shows that only the fringe solutions S5, S10 and the hybrid solution S7 fall within it. This might suggest a search for a possible new cluster of designs towards the top right corner of the shaded area.

3. EVALUATION

3.1. *Methods of Evaluation*

Evaluation is here understood to mean any method by which deficiencies in solutions can be detected *before* final manufacturing drawings have been started, *before* production begins, *before* the product has been sold, *before* it has been installed and *before* it has been put to use. The purpose of any method of evaluation is to detect errors at the stage when they can be most cheaply corrected, that is when the increasingly expensive processes of drawing, manufacture, selling, installation, and use do not have to be repeated in order to make the correction.

The traditional method of evaluation of engineering designs is by judgement, and by reference to the experience of engineers and draughtsmen, while the design is on the drawing board. When the right kind of experience is available, and when logical methods of detecting errors are too expensive or time-consuming, this is still the most effective method. The traditional engineering drawing can thus be regarded as a complicated two-dimensional model which permits the problems of manufacture, selling, installation, operation and use to be anticipated, and the design evaluated, at an early stage.

We are, however, already approaching a situation where engineering is

called upon to design and develop increasingly complex equipment of which little or no experience exists and for which engineering drawings do not provide an adequate means of evaluation. At the same time we are becoming accustomed to using more expensive, more logical and more exhaustive methods of evaluation such as field trails, market surveys, models, simulators, computers, operational research, pre-production, pre-engineering and product planning. The purpose of this and the following sections is to summarize what is generally known of these new methods and to show how they relate to the techniques described in these notes.

Evaluation by P-SPEC. The list of performance specifications (Section 1.5) should include a large proportion of the items to be tested by evaluation. The major task then consists of devising tests, trials, or other methods by which each design is checked against each performance requirement. It is helpful if the P-SPECS have been worded with such tests in mind, e.g. "accessibility *such that* terminals can be checked in less than 1 min"; "strength *such that* part A deflects no more than 0.01 in. relative to part B when maximum load is suddenly applied". Section 1.3 is relevant here.

Evaluation by judgement. In engineering design as it is today with new and unfamiliar logical methods being used here and there, with an increasing demand for the integration of previously separate components into complex interacting systems, with the continued raising of standards of performance and efficiency, and with the general lack of the time, development funds, and information which would make completely logical decisions possible, it is necessary to use a mixture of experienced judgement and logical decisions in the evaluation of any one design. These notes can be regarded as an attempt to bridge the very considerable gulf between these two methods and to overcome the inherent difficulties of using experience and logic side by side in one design problem. Some suggestions for mixing experience and logic in evaluation are given below:

Making judgements more precise. Stating judgements between limits; stating judgements in negative form (i.e. stating what must be excluded); putting judgements in order of importance using paired comparisons in an interaction matrix; separating opinions from facts based on experience by consulting several persons, or by logical question chains. All these methods have been referred to previously. Another is to list the consequences of *disregarding* each judgement.

Extending the area of judgement. The main method here is to bring the experience of many persons to each evaluation that has to be made. This can be done by a design review committee of senior and experienced persons and perhaps including a few persons of experience in non-engineering fields such as scientific research, personnel management, accounting, safety, etc. Such a committee would have no responsibility for design decisions. Its responsibility would be to list the possible consequences of the solutions and

decisions submitted to it for judgement and to predict the sub-problems to which any solution or decision may give rise.

Separation of logical decisions and judgements. When a largely systematic design method is being used it may well be helpful to organize a new "stematic design section", composed largely of young persons, responsible for using the method and making all the design decisions, but with the overriding rule that they must be able to demonstrate that all available sources of experience and judgement have been consulted—as in the design review procedure described above.

3.2. *Evaluation for Operation, Manufacture and Sales*

The whole of science and technology can be regarded as a search for exact means of predicting the behaviour of physical things. For this reason all the methods of calculation and experiment of which engineering training is composed are relevant to the evaluation of designs and obviously include far more than can be summarized in these notes.

There is, however, one major aspect of calculation and experiment which is largely absent from current engineering training and which is of central importance to a systematic design method. That aspect is the prediction of the behaviour of *large numbers* of related components, over *long periods of time*. Traditional engineering calculations are largely confined to the prediction of isolated events and separate parts of a design problem and leave to human judgement the assessment of the behaviour of the design as a whole. This may be the reason why so much engineering can at present be done with hardly any calculation at all.

We are, however, coming nearer to a situation in which evaluation and prediction of the performance of designs as a whole, and for their complete life spans, is falling outside the range of experience. Newer and more comprehensive methods of calculation are coming into being, largely because of the availability of high-speed computers. But before these sophisticated methods can be introduced into more intangible and complex areas of judgement it is both necessary and possible to make a start with simpler and more "manual" methods of logical evaluation, some of which are outlined below.

This "manual" or semi-logical approach to evaluation could be the responsibility of the separate "systematic design section" referred to in Section 3.1. Its basic methods of evaluation would be:

1. Collection and assessment of *available experience and judgement* (using the methods of Section 3.1).
2. *Simulation* (using any form of model making, drawing, analogue computing and experiment that is available and appropriate).
3. *Logical prediction* of all possible circumstances and situations which the design has to meet through its life (using interaction matrices and nets to check all the permutations).

4. *Pre-engineering development* (using small-scale but realistic facilities for pre-production, pre-sales and pre-operation in which unforeseen difficulties are discovered before full-scale production, sales and operation has started).

Section 4 entails the provision of fairly elaborate facilities of a kind not usually available to engineering development sections, as they are organized at the moment. These facilities are listed below.

Pre-production. The facility required is a small "production development section", separate from the main shops, but operating to the same standards of accuracy (or inaccuracy) and under analogous limitations. Production prototypes and parts should be made without any of the additional hand work or fitting that is usually expected in prototype manufacture. This section to be under a staff of engineers trained in design, method study, and production engineering.

Pre-sales. The facility required is a small "sales development section", separate from current sales and publicity work, which is in close touch with those sections of customer organizations that are most interested in future rather than present developments, and has the responsibility for getting pre-engineered prototypes accepted for trial by such customer groups. The section would make use of this situation to discover all the favourable and unfavourable sales reactions at this stage and would also prepare development versions of all the necessary sales literature, leaflets, advertisements, etc. This section would be the one most concerned with the making of realistic appearance models and with industrial design. It would be staffed by sales engineers with experience of systematic marketing methods and with some experience of design.

Pre-operation. The facility required is a small "operation development section", separate from current engineering. It would work in close contact with planning and research sections of customer organizations. It would seek facilities for the small-scale trial of pre-engineered prototypes for the expected range of operation conditions these facilities being provided by customers themselves. The section could be staffed by engineers with experience of design, systems engineering and research. It would be the section most concerned with research and with ergonomics.

REFERENCES

Many of the methods described in the above notes have appeared in various publications during the past ten years and particularly in the American journals *Product Engineering* and *Machine Design.* Some of these are listed below:

DU BOIS, G. B. Instruction in creative mechanical design, *ASME*, Paper No. 53–A–172 (1953).

FROSHAUG, A. *Visual Methodology*, ULM 4, Hochschule für Gestaltung, Ulm, W. Germany.

JONES, J. C. A systematic design method, *Design*, April (1959).

JONES, J. C. The design process, Internal Report of A.E.I. Industrial Design Conference (1961).

KAY, R. M. Steps in designing, Industrial Design Office, A.E.I. Manchester (1959).
MARPLES, D. L. The decisions of engineering design, Institution of Engineering Designers (1960).
MARVIN, P. Engineering the creative process, *Machine Design*, 10 January (1957).
MARVIN, P. Picking profitable products, *Machine Design*, 9 Feb. (1956).
MURDICK, R. G. The three phases of managerial planning, *Machine Design*, 13 April (1961).
NELLES, M. Deliberate creativeness in engineering, *ASME*, Paper No. 53–A–171 (1953).
OSBORNE, A. F. Applied imagination—Principles and procedures of creative thinking, Scribener's Sons, N.Y.
QUICK, G. G. Predict product performance, *Product Engineering*, 24 April (1961).
RANDSEPP, E. The creative engineer, *Machine Design*, 28 May, 11 June, 25 June (1959).
SHAPERO, A. and BATES, C. A method of performing human engineering analysis of weapon systems, WADC Technical Report 59–784, Office of Technical Services, U.S. Dept of Commerce, Washington, D.C.