THE
DESIGN METHOD

On behalf of Design and Innovation Group
University of Aston in Birmingham

Edited by
S. A. GREGORY

Springer

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PREFACE

THIS book about The Design Method provides a composite statement from different technologies on the nature of design, covering the principal range of activities of the designer, and a relatively unified structure of thought against which the work of the designer may be considered. A review of work and thought on the design process is given, together with an appraisal of systematic methods, and an analytical approach to the process of design, with the possibility of its extension by scientific research. The relationships between the behavioural sciences and design are also discussed. Finally, a glossary of design and a substantial, although not comprehensive, bibliography are included.

This pioneering effort provides practising designers with an opportunity to see their work in the round and to gain some new insights. Managers are offered a better comprehension of the problems and outlook of designers, with possible ways to more and better designs. To researchers some new challenges are given, and to industry and consumers at large the promise of a more rational approach to design. The attention of educationists is particularly directed to the fact that there is a design method which is at least as well defined as the scientific method, and poses more human and personal problems in its application. To the youth of today the book offers a rather intellectual glimpse of a world of skill, service and excitement, which is able to absorb to the limit the sum of human abilities. It is hoped that it will provide a foundation upon which students of design can build in the future.

The initial stimulus for this book came in 1964 at Scarborough, where a conference on education in design was being held. This was a good conference, but it seemed from the discussion that people were making assumptions about the nature of design which differed widely. Some people apparently saw design in terms of what went on to a drawing board; others took it to be something happening inside a designer's head, with the drawing board used only to help communication. There also seemed to be a preponderance of 'hardware' men and very few 'system' men.

It was decided to call a further symposium, with the intention of exploring in a relatively detailed way what the designer does. The symposium was to be open to designers and other interested people of all persuasions. Indeed, it was hoped to establish a common basis of agreement about the nature of 'the design method', using this phrase in the same way as 'the scientific method'. The Birmingham College of Advanced Technology (now the University of Aston in Birmingham) was chosen as the venue, in order that the existing Design and Innovation Group could be used as a working centre. At the time, this voluntary, but officially recognized, interdisciplinary group was unique in Great Britain. It draws its members from the technological faculties, from industrial administration teaching staff, from the College of Art, and informally from industry.

An outline of a possible programme was produced and invitations for contributions published as widely as possible through the engineering and other institutions, and the technical journals. Particular use was made of contacts with people connected with specialist 'networks' dealing with design throughout the country. Several of these have held conferences in the last few years.

Of great assistance were members of the Conference on Design Methods 1962 and the *ad hoc* Committee on Electronics Design of the Institution of Electrical Engineers. Other groups also helped but it would be out of place to give a full list here although it is recommended that some attention should be given to aiding at least the informal interchange of ideas between these groups.

On the basis of a number of voluntarily offered papers a pattern began to emerge, within which it became possible to seek out and obtain others. Certain papers offered were rejected. The common reasons for rejection tended to be lack of information relevant to the design operation, or the reproduction of what was obvious or known traditional practice. In some cases the papers were too specialized and therefore of restricted interest relative to the scope of the symposium.

The symposium took place on 21st to 23rd September 1965, and was attended by more than two hundred people drawn from the most diverse branches of technology and design. Papers were presented very briefly because preprints had been circulated. Discussion was fully recorded by tape.

This book is derived from the papers and recorded discussion. The papers are very largely those presented at the symposium with only minor modifications. The discussion has been subject to a marked amount of editorial work in order to provide readability. Significant points of discussion now appear as editorial comment and acknowledgment is made to contributors. Extra material has been written to give background, continuity, linkage and better coverage. The aim of the book as it now stands, is to offer to the interested reader co-ordinated information about the design method in the words of specialists in selected fields, and the possibility of pursuing the subject further and in depth. Attention is particularly directed to the use of the book for studies in the philosophy of engineering to suit requirements of the Council of Engineering Institutions.

To all who have contributed, whether by word, by action, or by encouragement, the editor gives grateful thanks. Above all thanks are due to Christopher Buck who carried the load of organization in his capacity of secretary of the Design and Innovation Group. Acknowledgments are thankfully accorded to the University of Aston in Birmingham for the use of numerous facilities and for providing a background without which the symposium would not have been able to occur and the book to appear.

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CONTENTS

Part I. The Design Method

Part II. The Human Perspective

Part III. The Elements of Design

Part IV. Design Techniques

Part V. Management and Design

Part VI. Design Research

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PART I

THE DESIGN METHOD

Chapter I

DESIGN AND THE DESIGN METHOD

S.A. Gregory

Introduction

This book is about design and designers. It is concerned with the process of design: a process the pattern of which is the same whether it deals with the design of a new oil refinery, the construction of a cathedral, or the writing of Dante's *Divine Comedy*. Much of practical design is humdrum but the same pattern persists.

This pattern of work, whether conscious or unconscious, is the design method. The design method is a way of solving certain classes of problem: relating product with situation to give satisfaction. A study of the design method helps one to a better understanding of design and to the possibility of bringing new forces to play in dealing with design. For the man in the street a study of design method means the potentiality of better products and greater satisfaction in those products.

Although the book cannot be comprehensive there is an attempt to deal with most of the features of design which appear to have some general significance to practical designers and students of design.

Design is concerned with making things that people want: with building up patterns which have value. These things have to be thought about and made. Design involves a thinking activity and an executive activity. This is true whether settees, space satellites, or sonnets are designed.

Designers

The most common understanding of the activity of a designer seems to be that he does something with his hands such as draw on paper, or mould a lump of clay. This is a design situation in which one man may be doing everything: he thinks about the products and then forms them. Most practical design today is split into many stages. Some people think about the general scope of the product; others think about details of the product; others specify ways in which parts should be made in workshops, and so on.

The initial work is largely done in the head and for this reason remains unseen. Only the products which appear in material form come to the eyes of the man in the street. It is largely from these products or from activities associated with their use that the value of a design may be judged. People therefore tend to think of design as an operation strongly related to material things, if not actually something poured into them. Designers, according to this simple view, either make machines which execute some obvious function, or they shape things to be pleasing to the eye. The former works at a drawing board and is concerned with getting objects made out of cast iron or mild steel; the latter has long hair, a peculiar taste in clothes, and plays about with clay and colours.

It is around such common conceptions that public discussion, political action, even sectional promotion, tend to cluster. When design is scrutinized at high level by an outsider it means either mechanical design, where the term mechanical has an ill-defined meaning, or it stands for 'appearance' design, which its practitioners call industrial design. These are only certain aspects of design in its totality. All kinds of engineers and technologists have an involvement in design. All artists, in whatever medium they may work, are designers. This is true of architects, electrical engineers, metallurgists, poets, works managers, as well as a host of other people and professions. Fundamental to this general idea of a designer is the building up of a structure, pattern, or system within a situation.

The Idea and the Action

People such as painters appear to develop their designs as they put them on canvas. In fact there seems to be some connection between the practical development of the pattern of paint under their hands and the fact of manual work. But although it is reasonable to expect some interaction between what they are doing and have done practically and their thoughts about the next strokes, it is recognized that the painter must be building up a design in his mind's eye before committing it to colour. Many painters prepare sketches first.

The painter develops a model in his head before bringing about its realization on canvas. This is probably true even with 'action' painting. Instead of using a separate sketch some painters make running alterations to what they have already painted and these alterations constitute the transition from a sketch to the final form. According to this view the painter has two kinds of activity at least: the construction of a mental model, and the transference of this mental model by hand on to canvas. To carry these out successfully he needs skills. Comparable sets of skills must also be accorded to all artists who produce material objects with their hands: the sculptor, the creative potter, and so on.

Since time immemorial pupils have learned skills by working with a master craftsman, a combination in which the pupils begin by practising manual skills directed towards the execution of ideas developed by the master. In architecture the separation between the generation of controlling ideas and the practical execution is implicit in the very name. Engineers such as Brindley, Rennie, Telford, Whitworth, became established as craftsmen, skilled in manual operations, before proceeding to the stage of master engineers. In this latter capacity they gave instructions to workmen by drawings or other means so that their visions might be fulfilled in iron or stone. Here, if the model was communicated by drawing, this drawing was an instruction.

It is partly from such a tradition that young people who wish to become designers are steered into periods of training in workshops and then in drawing offices. Fresh thought is due about the necessary reasons for such kinds of activity.

From seeing the essential element in design skill as residing in the hands of craftsmen, people began to see the preparation of the instruction to the craftsman as containing the vital operation. In architecture and engineering emphasis began to be placed upon the drawing board.

That the drawing board is not an essential feature in design is well illustrated by the example of James Brindley, as recorded by SMILES (1874). His brother-in-law said of the great canal-builder: 'When any extraordinary difficulty occurred. . . . having little or no assistance from books or the labours of other men, his resources lay within himself. In order, therefore, to be quiet and uninterrupted whilst he was in search of the necessary expedients, he generally retired to his bed; and he has been known to be there one, two, or three days, till he had attained the object in view. He would then get up and execute his design, without any drawing or model. Indeed, it was never his custom to make either, unless he was obliged to do so to satisfy his employers.'

Within the modern engineering industry most of the work which is done on drawing boards is to provide instructions to other people about the way in which material is to be shaped, joined, or assembled. This is largely carried out by men who have had some experience of manufacturing and production methods. In Great Britain they belong to the class of mechanical engineers although in the USA they are frequently termed industrial engineers, the name of mechanical engineer being used in a more restricted sense. Designers in the engineering industry who use drawing boards are likely to be more concerned with finding out the best way to develop the shape of a part or an assembly rather than with preparing drawings for the purpose of instruction. The drawing is used as a model for solving problems in design.

It should be noted that the drawing is likely to become less important in future, either as a means of communication or as a model for working out shapes or arrangements. Instead of using drawings which have to be read by a plant operator, it is already becoming worth while to provide machine-tool instructions by communicating directly to the machine by punched tape which provides numerical control. Experiments are being made on working out shapes on a cathode-ray tube presentation. This kind of shape presentation may be readily converted into a punched tape communication.

But the production of the major ideas – the guts of design – is usually done by people at least one remove from the drawing board. The distance from the drawing board depends very much upon the type of design which is being undertaken. In mechanical engineering design, which may be concerned with such things as motor cars, machine-tools, refrigerators, boilers, *etc.*, there are usually at least two stages of design work. In the first stage the requirements are worked out for the fulfilment of the function of the product. Thus, for a motor car, the number of seats and the space needed for getting into the seats and for comfort while in the seats, and the baggage space must be settled; the speed and manoeuverability of the car have to be agreed, and so on. Only when these functions have been determined and their balance worked out is it possible to consider alternative ways of carrying them out in 'hardware'. From the preparation of schemes for the hardware, it is possible to proceed to the preparation of drawings for manufacture and assembly. Here, function design and production design can be identified.

In some other kinds of engineering, in chemical engineering and in electrical engineering particularly, it is possible to find at least three stages of work. The primary function design is done by one kind of specialist engineer; this is then followed by a mechanical embodiment design; in turn comes a production design.

Change – Evolution and Revolution

To many people in design this view of the several stages may not be immediately familiar. This is probably attributable to the fact that most of practical design activity is involved in modification, in making relatively small changes to products or machines which already exist. This is essentially evolutionary design. Such changes as take place occur within a well-defined situation. Even the designer occupies a well-defined position within a closely structured company arrangement, quite typically consisting of vertically defined functional divisions, such as sales, production, finance, and engineering.

People in design who are associated with major new projects are, on the other hand, likely to be acutely aware of the interdependence of the various classes of engineering design. Indeed, it is fair to say that much of the interest in the new thinking about design comes from people who have this kind of involvement. The types of system with which these new projects are largely concerned, are the relatively complex arrangements of equipment needed to perform some major economic function. Such large systems (the range of which is considered later in the book) may include power stations, intercontinental telecommunication networks, new towns, *etc.* In their own right, these projects are of such magnitude as to demand the most careful thinking about their design, so that the best use may be made of social resources. Thought about specific design leads to thought about the nature of design in general. Many of these large projects are essentially copies of projects which have gone before, but suitably adjusted to suit the needs of the local situation. Every now and then, however, radically new projects have to be faced. This leads to even more determined thought about the fundamentals of design.

In the USA there is a clear connection between the space programme and fresh thinking about the nature of design. In Great Britain much of the new approach may be related to those sections of industry which are undergoing expansion, and the professions associated with them. There is also, both in the USA and Great Britain, a considerable impulse from branches of study such as ergonomics which were called into being to deal with problems of man – machine interaction.

In Great Britain it is likely that the tasks of economic expansion, particularly along the lines suggested by the National Plan, may be such as to put considerable strain upon the limited resources of design capacity. According to the figures put forward regarding the preferred extent and directions of expansion, the shortage of design capacity is likely to be felt in the field of consumer durables (cars, houses, *etc.*) and probably even more in the design of large projects such as chemical plants. The chemical industry is scheduled as the largest recipient of capital investment in the industrial sector as a whole. Power production is the most important manufacturing activity in the public sector. Behind such requirements for design, expressed primarily in terms of design of the relevant chemical or electrical systems, come the civil engineering problems, the manufacture of the necessary hardware, and the assembly and commissioning at site.

Universal items such as electronic computers and machine-tools, serve a wide range of industry and in that sense are critical. Their design, once achieved, continues to be reproduced in manufacture for considerable runs. On the other hand, the complex one-off systems such as oil refineries, transport systems, *etc.*, require to be designed afresh for each case, and furthermore the assembly system has to be newly worked out. It is this kind of operation which soaks up design capacity.

The study of design is therefore critical in terms of national economic success and survival.

The Design Method and Systematic Procedure

The conscious identification of the design method is quite recent, although precisely when the concept appeared is not clear. It is important for designers to become aware, consciously, of the existence of the design method. The design method and its practice distinguish the engineer from the scientist. Each is a problem-solver but has different kinds of problem to deal with. Put simply, the scientific method is a pattern of problem-solving behaviour employed in finding out the nature of what exists, whereas the design method is a pattern of behaviour employed in inventing things of value which do not yet exist. Science is analytic; design is constructive.

Problem-solving is a very general kind of activity; a simple introduction is by HODNETT (1955). It can be regarded as the search for and discovery of means to achieve or prevent transformation from one state of affairs to another, where the affairs may be abstract or concrete. Although problem-solving is so general in character there are a number of relatively systematic approaches which may be used. An example used in industry is the 'systematic appraisal' technique. This is at the basis of what is known as work study. The most widely-known class of problem-solving activity is the scientific method. In dealing with the problem of investigating what exists in nature, the method involves the generation and testing of models of parts or the whole of the universe. The scientific method has attained such a reputation that it now tends to be seen as the prototype of all other kinds of problem-solving activity.

The human brain is endowed with many abilities which may be devoted to problem-solving. In particular, GUILFORD (1959), has shown how they may be classified in terms of the categories: perception, memory, convergent thinking, divergent thinking, and judgment. Within these classes of operation the intellect may deal with contents which are either concrete (as exemplified by the person who is a 'visualizer'), symbolic, semantic (in this case the exemplification is through the 'verbalizer'), or behavioural. The contents may deal with such products as units, classes, relations, systems, changes and implications.

The central activity of engineering, technology, and art is the design method. Since this is a kind of problem-solving it will have resemblances to other kinds of problem-solving. Technologists, without conscious knowledge, frequently switch from the design method to the scientific method. Recently, because of the confusion which exists, (a confusion which has had undesirable educational and other consequences) there have been welcome attempts to differentiate between the activities of science and those of technology and engineering. Particularly readable are the little books by SPORN (1964) and KRICK (1965).

Many recent authors have described the design method in considerable detail and later chapters of this book pursue the discussion. A compact description is given by ASIMOW (1962) and, within a perspective of system engineering, by HALL (1962). These descriptions are based upon much discussion within a background of practice.

This concentration of attention upon design has brought about a considerable interest in systematic procedures for design. Part of this interest in systematic procedures has come directly from work study; but the fact that the design method may be identified leads to the study of the particular techniques which skilled designers use and the organization of these techniques into systematic methods which may be suggested to other designers or those in training.

It is important to recognize that systematic procedures will not by themselves produce outstanding design. While they may be seen as a way of raising the general level of competence in journeyman design and as a check-list of procedures for other designers, they carry intrinsic danger. This is the danger of routine behaviour, of adherence to a disciplined drill. To make provision for dealing with this it is important to emphasize repeatedly the need for freshness and the creative approach to the situation and the task.

Human Satisfaction and the Design Situation

The end of all design is human satisfaction. If a design fails to deliver satisfaction it fails as a design. The early civil engineers who, a century and a half ago, first saw themselves as professional engineers, described their function as the harnessing of the great powers in nature for the service of man. Just as manufacturing concerns have tended to become production orientated, so have engineers tended to become obsessed by strictly technical problems. The user and customer have become neglected. Partly this has come about from the specialization of functional departments within industrial companies. An even greater pressure has probably come from teaching institutions which have concentrated upon technical knowledge and its acquisition.

This tendency to disregard the consumer is not only a retreat from the spirit of engineering but it carries the possibility of national disaster. In a competitive world it is the mastery of the market which prevails, and the mastery of the market means design for the consumer. The market not only represents the consumer; to the designer it is also the challenge and the opportunity. The need of the times is for the designer to be turned towards the market. All those means which may be legitimately exploited to increase satisfaction should be at the disposal and command of the designer, who should see the consumer as his primary target. For this reason the reader is directed towards that section of this book which deals with human satisfaction and the opportunities presented.

The Elements of Design

When the practice of design is first looked into in some detail and with some intellectual refinement, it can be a disturbing experience. People who have not previously taken part in practical design may wonder what is being discussed. Practical designers of the 'no nonsense' variety may also have distinct misgivings. Indeed, some of them may be provoked to scorn and ridicule. Chapters 10 to 16 of this book may prove difficult reading to newcomers and it might be advisable for them to avoid detailed examination of this section on the first reading. The difficulty lies in the fact that it is concerned with an examination of the process of design and its successive stages in a theoretical manner. It is concerned with advancing a model of the process of design and with investigating the principles and basis of each of the stages.

The practical value of this kind of approach lies in the production of a model or set of models of design behaviour. These models may be tested by experiment or against practical observation and, with suitable validation, may provide the foundation for practical advice. Indeed, most of the methodical procedures which have been put forward for helping design rely upon some analysis of this kind.

It must not be assumed that all is known about the elements of design just because they may be expressed in the form of diagrams. These diagrams represent a relatively simple kind of model of the design process. The detailed course of design in a particular situation may be much more complex, even for a small product. For very sophisticated and novel designs the process may be difficult to communicate because of the inadequacy of the concepts which are currently used. It is likely that in some of the finer detail it will only be possible for one designer to talk to another rather than to people at large. A stage is reached in design where a series of moves has to be made rather like those undertaken by skilled players of chess. Strategies must be adopted.

The study of design strategies is only recent and is not dealt with in Chapters 10 to 16, although it undergoes some examination in Chapter 32 in particular. There is a more detailed discussion of the matter by GREGORY (1966). These strategies, which are procedures for dealing with complex and uncertain situations, are phenomena which may be clearly observed in practical design. A number of them has already been recorded as the result either of reflection upon practice or, in the past few years, as the result of specific observation of design. Some of the methodical design procedures already have a selection of the more obvious strategies built in.

The study of the elements of the design process, although at first appearing rather abstract, is, in its outcome, severely practical.

The Practice of Design

A person may build up his knowledge of the way of design by reviewing what has occurred in practice within his personal experience. To broaden the basis of knowledge he studies the work of other people. Eventually he constructs a picture in his mind of the pattern of behaviour during design. Other people do the same kind of thing. Eventually it becomes possible to generalize this kind of experience and to pass it from one person to another. This communication will almost inevitably use models of one kind or another. The models will not only represent one person's view of things but will provide opportunities for working out examples in a rather general way. Chapters 17 to 21 deal with models of various kinds used in design, either with specific examples of models in practice, or with more general models. These chapters, in fact, show the use of models in the problem-solving activity of design, in design for function and in the formulation of a product.

After the practice of function design through the use of models, a practice which is concerned with development of design up to the point that steps may be taken towards its realization in some material or mechanical form, comes that region of design which is more familiar to many working designers, *i.e.* design for realization.

Design for realization is concerned with all those aspects of practical design which include the selection of the best kind of mechanical features to provide for the carrying out of the required function; the selection of the materials which give the best performance within the limits of the situation; the choice of the most suitable methods of manufacture and the reviewing of the design within the terms of manufacture; the communication of these decisions to the people or machines which are to carry out the detailed fabrication of the components and parts and subsequently to the people who have the task of putting the parts together in a working system. For many practising designers this is the most important part of design. Such is a matter of opinion. Certainly it is only part of the total picture: function and system designers obviously see the situation differently. But in the last stages, in order to be useful, all design has to pass through realization design. It is a necessary part of design.

Even at the level of realization design the general principles of design thinking hold. Here the opportunities for methodical procedure and for creativity reveal themselves, often delivering substantial rewards. It is in this area that the recent emphasis on value engineering and analysis has made successes. This has been discussed particularly by MILES (1961) and in a series of articles in *Product Engineering* (1965).

Because much of the work in realization design is well understood and well established it tends to be adopted without questioning. Value engineering has shown the significance of questioning, as did work study before it. The perpetual questioning arising from a scientific approach to this area of design carries with it the promise of further returns. These returns may not come directly from the practised procedure but from the invention and development of new mechanical or electrical techniques to help the designer. But the designer needs to be concerned not only with design techniques, not only with mechanical or electrical assistance, but also with the potentialities of the new materials, which may substantially change the basis of realization.

All practical design, whether at the system, the function, or the realization level, is likely to be the activity of some organization. The way in which design interacts with management is the concern of Chapters 27 to 31. Here is discussed the way in which design is the practical expression of that part of management policy concerned with the preparation for the exploitation of opportunities held to be favourable to the company concerned. In order that the design carried out in the organization fulfils the general objects of that organization, the policy dealing with design has to be clearly thought out and effectively transmitted. The opportunities for the company lie not only in the market as such but in the minds of its designers. How should the interchange of thought and decision about such opportunities be best arranged? Designers do not achieve their best work as a general rule under dictation and rigid discipline. How is the most productive use to be made of designers?

The need for innovative design to be an expression of the total attitude of an industrial company is important. Design is not solely the function of the designers. Other skills and other departments can help and assist in the development of a general innovative atmosphere. Most important as a contributor to this is the attitude of top management. Unfortunate indeed is the designer who faces resistance at all levels. Unfortunate, too, is the company which has this kind of creeping paralysis, since in the long run it will die from it, as have many well-known British companies in recent years.

Given the correct attitude for the reception of innovative design, in support of a policy clearly set out to take advantage of the opportunities which exist and which will come into being, it is necessary to provide for the free and unimpeded flow of information and ideas throughout the organization. Designers must have the data that they need available in the correct form at the time required. They must have clearly defined boundaries of decision which competently reveal their responsibilities within their own company and towards the consumer. They need the opportunity to discuss and clarify whenever it is reasonable. The essence of these requirements is an attention to the communication system of the organization. So important is this need that in cases of new projects the company organizational structure has to be modified in order to make certain of maximum ease of communication.

This section of the book concludes with Chapter 31, which deals with techniques of evaluating and improving design activity and effort.

The Scientific Study of Design

This book, as a whole, is concerned with the theme of the design method. It begins with a statement of the underlying thesis and goes on to deal with the principles as known and with the important practical procedures. Chapters 32 to 35 are concerned with the development of the empirical study of design, with speculations about the connection between various types of design, and with proposals for research into design, both in respect of design activity as such, and to aid the development of new mechanical and electrical aids. Chapter 32 is a comprehensive review of the recent development in thinking about design.

Conclusion

You are asked to read on and take what advantage you choose of this attempt to put design into a new perspective, both intellectual and practical – an attempt to show the scope and challenge in the heart of engineering.

Chapter 2

THE DESIGN METHOD IN PRACTICE

R.J. McCrory

Introduction

Just as in Great Britain, the designer in the USA has been in danger of becoming the forgotten practitioner of technology. Because he must, almost by definition, be a generalist, the designer has been discounted in favour of the specialists in more tangible areas. But in the USA this tendency to undervalue the designer seems now to be reversing in both industrial and academic circles. In industry, the designer systems manager is being rediscovered as the man who can grasp and accomplish a comprehensive programme with all of its involved and nebulous problems. Universities are realizing that design is, if anything, more intellectually and academically demanding then many of the more specialized areas of study.

The challenge imposed by this trend is one of both quantity and quality. Obviously, more designers competent to fulfil the demands of systems management are needed and, hopefully, outstanding students can be attracted to design presented as a scientific endeavour which, in fact, it is. Both industry and the universities are responsible for the quality of design – industry for demanding of the designer performance of a high scientific standard, and the universities for conducting further research and offering challenging and useful courses in design.

The Scope of Design

Design is considered as the process of selectively applying the total spectrum of science and technology to the attainment of an end result which serves a valuable purpose. It is the segment of engineering which devises and develops new things, in contrast with other segments which emphasize the solving of problems or the generation of engineering information. The responsibility of the design engineer is to use the maximum powers of creativity, judgment, technical perception, economic awareness, and analytical logic to devise uniquely useful systems, devices, and processes. His function is usually not to originate the basic scientific building blocks, but rather to utilize them so that the result is a useful creation.

Design must adhere to a plan which has objectives involving cost, performance, amount of effort required for attainment, probability of success, and even aesthetics. The fact that design must traverse a closely evaluated path, starting from a well-considered if not urgent need statement to a functioning achievement, requires that it follow a methodology. By methodology is not meant the tricks of the trade such as drafting competence, or analytical ability, or, for that matter, a flair for brainstorming. Methodology in design is rather the framework for the design process within which a sequence of action steps can be based and from which check-points to evaluate progress can be established.

An important influence in the renewed attention to design is a general agreement on the part of Americans engaged in the study, teaching, and practice of design that a unified methodology of design does, in fact, exist. Although different authors have presented various detailed descriptions of the process, these descriptions are essentially all similar to the so-called 'design method' summarized here which, in turn, is an adaptation of the scientific method of McCRORY (1963).

Structure of the Design Method

Although the design method is similar to the scientific method, it has not been as carefully defined nor historically as well established. Nevertheless, the design method is as inherent to the design process as the scientific method is to scientific exploration. Designers will do well to recognize its structure so that the design method can be used consciously to clarify some of the costly 'mysteries' of design.

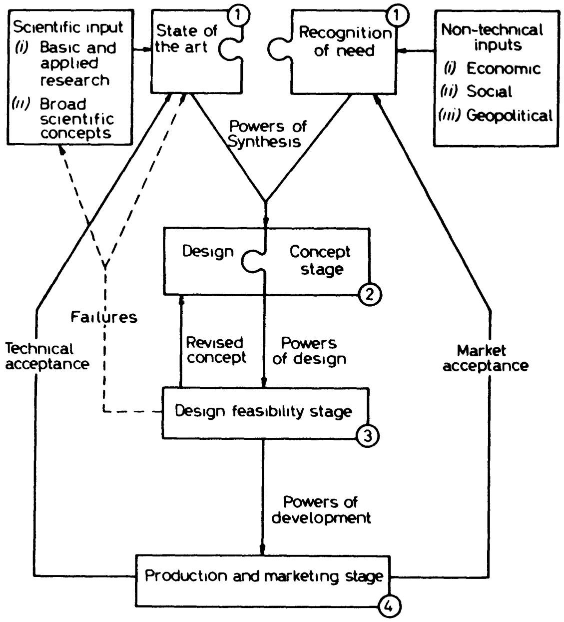

Figure 2.1. Graphical representation of design method

The design method, graphically described in *Figure 2.1,* is a closed loop, with experiences gained at various stages during the execution and completion of the process providing the basis for subsequent steps. The method is compounded by multiple interconnecting steps and auxiliary stages, but these are only ancillary to the basic methodology and can vary depending upon individual situations.

State of the Art and Recognition of Need

The starting point of the design method is more comprehensive than that of the scientific method. Unlike fundamental scientific research, design is motivated by need rather than by curiosity. Therefore, in addition to requiring knowledge of the state of the technical art, the design method requires recognition of a need which warrants an investment of effort and funds.

Recognition of need can be considered the marketing input to the design method. Whether government or industrial needs are being considered, the designer must realize that much of the input required to define the need is not technical, but rather socio-economic-geopolitical. Therefore, the designer must appreciate those key non-technical factors which are significant in defining whether the results of his design work will fulfil a basic social, economic, or security need. With this appreciation, the designer is better qualified to extrapolate current requirements and creatively anticipate tomorrow's needs.

Given a need-oriented assignment, the designer can encounter a serious point of personal vulnerability. The purpose is not, as he might prefer, to provide a result which is technically self-gratifying and elegant, but from which the only pay-off will be a technical paper to his peers. The purpose is to produce something which is truly useful in satisfying the defined need. Because designers are required to satisfy profit or security motives, the definition of need is critical to the design method and each succeeding stage must be planned and judged on the basis of the need.

Along with the recognition and definition of the need, the design method requires an appraisal of the pertinent state of the art. State of the art includes materials capabilities, phenomena understanding, and previous design experience. However, as important as previous experience is, if designers are too limited in their conception of it, design progress can be reduced to a series of small improvements. The design method requires that the designer tap into the total spectrum of technology with the objective of obtaining the greatest design advance consistent with the state of the art, wherever the art may exist. Experience which is available in technical or product fields foreign to that of the designer can often suggest the most advantageous design approaches.

But perhaps even more significant to design advance is the input which can be obtained from research. As materials are devised and phenomena quantified, new raw inputs to the design method are made available. New scientific concepts open up fresh areas for design exploitation. The design method, therefore, necessitates keeping open a direct link to the resources of scientific and engineering research. The degree to which the designer can intercept the latest scientific information can determine the extent to which he can make significant design advances.

The Design Concept

A design concept is created when, through the designer's powers of synthesis, a recognized need and technical capability as represented by the state of the art are matched. When the designer can arrange technical art into useful combinations which form a system satisfying a need, he has a design concept.

Matching can originate from either the need or the art. Given a defined need, the designer can search the art for the inputs which can be synthesized to satisfy the need. Conversely, there are many concepts which are originated largely on the basis of known art, and the concept stage is attained by finding a need which can be fulfilled. The latter approach to design conception is the principal justification for the massive engineering research being conducted in energy conversion, materials, and other generic fields of technology.

If an idea does not satisfy a need, a design concept as defined by the design method does not exist regardless of how clever or novel the idea might be. Nor does a concept exist when a design which would satisfy a need requires a capability beyond the state of the art. The principal gain to be derived from the work done is feedback to the research laboratories.

The designer can fulfil his synthesis function by an orderly procedure (McCRORY, WILKINSON and FRINK, 1963). He first analyses the need in considerable depth, perhaps allowing the need analysis to suggest a design concept. He then spatially visualizes systems which are advantageous combinations. Or he might utilize a further technique which is not as broadly recognized: this is to explore analytically the area of design interest, manipulating generalized mathematical expressions with the hope that unique design approaches will be derived which would not be apparent from only spatial analysis.

Attainment of the design concept stage of the design method means that a design approach has been derived with the potential of satisfying the need as well as the potential of being attained within the state of the art. Many ideas may be rejected by the designer before he arrives at one which qualifies as a design concept. On the other hand, he may finally have available more than one design concept showing attractive potential. At the design concept stage, the concept need not be described completely. Rather, it may be expressed in terms of functional requirements or 'black boxes'. The key criterion is that the concept has sufficient potential to justify further effort in designing the individual elements of the system.

Design Feasibility

The design concept stage having been attained, the next step is to establish design feasibility. Feasibility is established by determining whether all of the necessary functions of the system can be worked out and whether, when the design is in detail form, it still is attractive in terms of the need and the probability of successful attainment. To go from the design concept stage to the feasibility stage means to convert the design as described in its functional form to specific elements. The steps (CRESS and CHEANEY, 1963) which may be used in this conversion process include:

(1) Definition of the concept in terms of its optimum combination of functions.

(2) Expression of detail design requirements in terms of functional and/or performance specifications.

(3) Design of specific elements to meet specifications (to be done in accordance with design method using specifications as need statements).

(4) Trade-off analysis comparing design alternatives and, if required, revision of specifications.

(5) Critical experimentation to test specific questionable aspects of the design concept.

(6) Operation of experimental prototype to confirm adequate functioning of total system or sub-systems.

Frequently the design concept fails to reach the stage of feasibility because the technical problems cannot be solved successfully or because the concept does not fulfil its apparent potential of being attractive in terms of the need. The probability of this happening should be reduced if designers conscientiously go carefully through the prior steps of the design method. When failure does occur, it is necessary to return to the concept stage and revise the concept in the light of experience gained. However, if failure is complete, the most that can be salvaged is the failure experience which can be interjected into the state of the art as a guide to subsequent design programmes.

Production and Marketing

When the designer is convinced that a feasible design is in hand, he is ready to move on to the next stage in the design method. This is the development of a design which can be produced successfully and marketed. In actual practice, development tasks are extremely demanding in terms of engineering skills and they usually involve the major expenditure of funds and time.

Within the framework of the design method, the development step is still very much a design function (MCCRORY, 1965). The designer remains responsible for perfecting the design in terms of performance, reliability, and cost. Although specialists in value analysis, tooling, reliability, and marketing may more prominently enter the picture, they cannot recover success if the requirements of the earlier stages of the design method were not validly satisfied. Presuming skilful engineering and marketing, the development steps, although costly, are not highly risky. The mistakes which lead to disastrous failures are more likely to occur at the stages when decisions regarding need, concept selection, and feasibility are made.

The loop of the design method closes when the design is judged a technical and marketing success. This experience in market acceptance extends the understanding of need and invariably leads to the identification of new areas of need. The technical successes and failures expand and temper the state of technical art and are inserted into other design programmes.

Variance in the Design Method

An idealized description of the design process has been presented. If individual design programmes were discrete entities, the design method as described here in skeletal form would be accurate. In actual fact, design efforts seem to blend into one another to the extent that a complete progression of the design method is difficult to recognize. As actually practised, design progress involves a pattern of superimposed programmes, each subject to the requirements of the design method. This pattern may include:

(1) Design programmes in which the outcome is the selection of a means of approaching a broad national or industry need. This type of programme is being applied to the transportation problems of the American east coast megapolis. The application of the design method here will involve overall systems concepts whose feasibility will be established by computer analysis prior to operation of prototype hardware. The outcome will be need statements for other design programmes.

(2) Numerous design programmes which originate from the same need recognition. Some of these programmes will be parallel programmes conducted by different design groups searching for the same end result. Theoretically, application of the design method should result in the same outcome for each programme. But the personalities and backgrounds of the individual design groups are so important to the functioning of the design method that results which are different in both approach and quality are inevitable.

(3) New programmes which are initiated before an original design programme is completed and which have as their objectives the improvement upon the results of the first programme. The demands of progress often cannot wait for the sequential completion of related design programmes.

(4) Auxiliary programmes on sub-systems and components which are part of an original overall programme. The design concept having most potential may require an element which is identified as beyond the state of the design art. But the attractiveness of the concept may warrant the risk of initiating a separate design programme to expand the state of the art. The designing of individual functional members becomes a number of sub-programmes calling for use of the design method.

Technical Planning – A Means of Defining Design Opportunity

If design is to be technical effort intended to serve a purpose such as devising a profitable product, then *a priori* judgment must be made regarding the problems worth working on and the opportunities which offer the most promise. As defined by the design method, need definition is the critical first stage of a successful design programme. Because technology has become so costly and failures so devastating, considerable effort can be justified in selecting the design objective in which an investment will be made and the plan that will be followed. One approach is termed 'technical planning'.

Technical planning is a process of deriving possible courses of design activity by recognizing the technical and marketing environment toward which the design will be directed and then systematically evaluating alternatives. This type of endeavour should be a continuing programme conducted co-operatively by the design group and other decision-making circles within a company. However, technical and marketing inputs must be brought together within a framework of corporate objectives originating from top management levels. Thus, really effective technical planning involves corporate policy makers, sales and marketing personnel, research staff members, and designers. Technical planning cannot succeed without unique contributions from the designer – contributions of which most designers are not aware or which they do not know how to make.

Figure 2.2 is a PERT* type diagram of a rather comprehensive technical planning programme for a company which has the corporate objective of being on the product forefront in its field of marketing endeavour. This field is presumed to be one which is technically demanding (such as prime movers, electronics, or petrochemicals) although

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* PERT = 'Programme Evaluation Review Techniques' developed for the US Navy.

technical planning of a somewhat more limited scope is being used effectively in marketing areas which, on the surface, would seem more mundane (such as home appliances and heat exchangers).

Figure 2.2 shows a series of action steps or tasks in a technical planning programme.

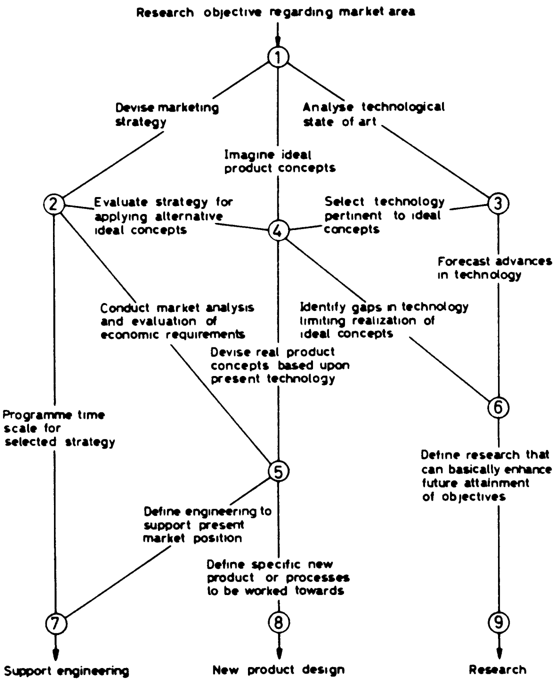


Figure 2.2. Task diagram for technical planning programme

The starting point is the stated objective: *i.e.* this company intends to attain and maintain a pre-eminent position in the vehicle prime mover field and therefore wishes to plan a technical investment that will achieve this objective.

The task tree of *Figure 2.2* has three principal branches: the left branch is principally marketing; the right is research. The core or central branch, however, is the work of designers. The marketing tasks provide inputs which say what can be sold in the market place and how it should be sold; in addition, these inputs provide economic criteria with respect to the technical alternatives. The research oriented inputs from the right indicate what can be done on the basis of the technical state of the art.

The designer proceeds through a series of tasks starting with task (1) – (4) during which he devises one or more 'ideal product concepts'. These ideal concepts are the best that can be imagined in terms of product attractiveness. Restraints regarding attainability or internal workings of the ideal concept should not be imposed at this point, although the designer cannot, of course, be given license to violate basic scientific laws. Usually the ideal concept is described in terms of product characteristics (the efficiency, size, weight, cost, configuration, durability, *etc.*) which would be thought ideal for the type of product being considered. If the designer does not make facetious specifications (for instance efficiency of unity, no weight, no cost, indefinite life) he can in expressing an ideal concept describe a product which would have optimum attractiveness but be a realistic challenge to innovative design.

The designer can also describe in similar terms the best commercial achievement in this product area. Then the gap between the description of the best existing product and specifications of the ideal concept represents the challenge to innovation and product improvement. If this gap is small, either *(i)* the ideal concept does not suitably represent product opportunity, or *(ii)* opportunity does not, in fact, exist. If it can be shown that opportunity does not exist, it may be necessary to recommend to corporate management that objectives be revised.

Having described the ideal concept and having decided where opportunities seem to lie, the designer proceeds to task (4) – (5). Now he must devise real design concepts. For this he needs realistic marketing targets from task (2) – (4) and a thorough reading of the technology from task (3) – (4). He must then formulate real product concepts using the synthesis techniques of the design method. It is important for the designer to devise several alternative concepts which can be subjected to subsequent evaluation. Some of these concepts may represent relatively small advances but they may also involve relatively low risk. Other alternatives may offer the potential of major steps toward the ideal concept but involve greater risk. Such alternatives are required if the technical planning is to result in the identification of the preferred business opportunity.

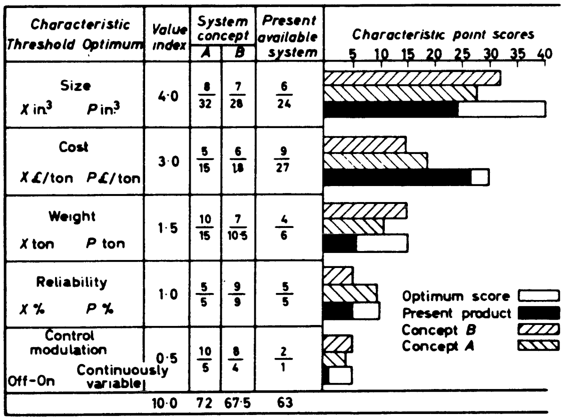
The next task for the designer and his cohorts in technical planning is to evaluate design feasibility and to select the concept which will offer the best business opportunity. In order to undertake task (5) – (8), the designer and market analyst must work very closely to estimate the saleability, market strength, and return on investment potentials of the alternative concepts. The designer must also substantiate the feasibility of the possible concepts to the extent that he has reasonable confidence that further investment is technically justified.

There must, of course, be a considerable amount of subjective judgment in selecting preferred business opportunities. But the value of comparisons can be greatly enhanced by proceeding through a deliberate rating of the potential of each possible concept with respect to the product characteristics used to describe the ideal concept.

The comparison procedure can take the form of scoring for each characteristic and arranging the scores in the form of a matrix. The matrix would be so designed that the overall or lumped performance of each candidate concept would be readily calculable, and also so that the respective advantages and disadvantages of the candidate systems can be perceived. *Figure 2.3* is a sample of the kind of display which has been particularly effective.

In this figure, various characteristics of a hypothetical product are shown ranked by order of importance. The degree of importance is indicated by the index number assigned to each characteristic. In this hypothetical case the evaluator has established that the most important characteristic of the product is small size; in fact, the value index numbers show that he regarded this to be four times more important than having optimum reliability, and eight times more important than having a continuously varying control system.

Two new product concepts *A* and *B* are being compared against a commercially available system and the optimum characteristics of the ideal concept. The effectiveness of each one is judged by assigning a number from one to ten for each characteristic. An effectiveness number of one means that the product performs at the threshold level, whereas ten means the performance is optimum or ideal. In this type of display it has been found convenient to note the threshold and the optimum values for each characteristic in the block with the characteristic name. The product of the effectiveness number and the value index is the score for each system with respect to each characteristic. The assigned effectiveness number and consequent score are shown in each characteristic block for the two new concepts. Note that the value index quantities have been so chosen that the lumped score for the optimum overall system will be 100 points. In this case,



Characteristic Threshold Optimum	Value index	System concept A	System concept B	Present available system
Size X in^3 P in^3	4·0	$\frac{8}{32}$	$\frac{7}{28}$	$\frac{6}{24}$
Cost X £/ton P £/ton	3·0	$\frac{5}{15}$	$\frac{6}{18}$	$\frac{9}{27}$
Weight X ton P ton	1·5	$\frac{10}{15}$	$\frac{7}{10·5}$	$\frac{4}{6}$
Reliability X % P %	1·0	$\frac{5}{5}$	$\frac{9}{9}$	$\frac{5}{5}$
Control modulation Off-On Continuously variable	0·5	$\frac{10}{5}$	$\frac{8}{4}$	$\frac{2}{1}$
	10·0	72	67·5	63

Figure 2.3. Product effectiveness scoring matrix

both the new concepts outpointed the commercial system, with concept *A* having the best overall advantage.

Considerable guidance would be obtained by the designer from a study of the scores and the bar graph display at the right of *Figure 2.3.* For example, it is clear that the greatest opportunity for technical advancement over the available commercial product lies in conceiving a system of reduced size since the commercial system falls well short of optimum in this respect. Both of the newly conceived systems have some measure of advantage here, although it is not particularly dramatic. On the other hand, both new concepts evidently fall short of the commercial system, and well short of optimum, in the important category of cost. With respect to the other characteristics, the new concepts are highly effective but derive little advantage thereby because of the relative unimportance of these characteristics. Thus, the conceptual objective becomes quite clear: the designer must envision a system which will retain the size advantages already in hand and which will cost less. He has some conceptual leeway in striving to do this since he may be able to devise a way to trade off control modulation for cost.

At the completion of task (5) – (8), there should be the intelligence necessary to make decisions regarding new product design activities and substantial information available to the designer to guide him to success. From this comprehensive technical planning programme would also be derived plans for providing engineering resources needed to support the company's present market position and for selection of research projects to strengthen the long-range corporate position in its market area.

Conclusion

As indicated by the preceding paragraphs, there is in the USA a distinct trend toward the use of method and discipline in design. This is considered by the author to be a favourable development because of its potential benefit to both the education of designers and the execution of more demanding design work. In education, the treatment of design as a discipline makes it more attractive to students and provides the teaching faculty with tangible subject material. In industry, the design methods being developed and gradually adopted provide the tools with which talented designers can extend their efforts into new areas and which will give designers more confidence in the validity of their work. Although new developments in design methodology are still far from fully adopted or always effective, there does seem to be increased interest stimulated by demonstrations that creative design can be approached by orderly and even predictable methods.

However, regardless of the sophistication of methods which are devised to enhance the effectiveness of the design function, they must be recognized for what they are: only tools to be used by the designer. The key to brilliant design remains the designer himself with all his intangible design capabilities such as intuition, judgment, determination, courage, spatial vision, and imagination. Some engineers have these qualities and can therefore become natural designers; others do not and probably cannot be trained to serve other than ancillary roles to design. There can be real concern that natural designers are not being recognized and developed by the 'apprenticeship' approach which trained many of the present vanishing breed of designers. In fact, with the premium placed on highly science-oriented graduate level education, there has been criticism in the USA that design potential is being snuffed out. It has been Battelle's experience, however, that recent graduates of America's engineering colleges are unusually capable of doing the most demanding design work, and have a flair for the original and a capacity for analytical rigour that is refreshing. With this new generation of designers, the effort being exerted in the derivation of advanced design methods is not being wasted.

Chapter 3

DEFINITIONS AND METHODOLOGIES

W. E. Eder

Introduction

Design in its fullest meaning is the top role of the engineer (HRONES, 1960). Before any work of human skill can be produced it must be imagined. In essence, it is this human power of imagining something that did not exist before that is termed 'design' (HARVEY, 1950). This chapter is therefore concerned with an outline of the knowledge, skill and imagination required by the designing engineer; the progress of a new piece of equipment (in the abstract) is traced from the original idea up to the point of production; the probable approaches adopted by designers in solving engineering problems are indicated, and the use of various 'tricks of the trade' to help in this process; finally where these tricks are useful in the context of a small selection of technologies is shown.

The basis of much human activity lies in a full and broad education, consisting of a balanced view of the sciences, technologies, the arts, and the crafts (*Figure 3.1*). Two dangers of a lacking balance in education are obvious: firstly of overlooking possible connections, analogies, *etc.*, and secondly of overlooking or ignoring the fellow human being.

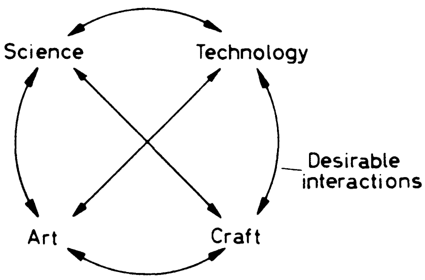


Figure 3.1. Ideal of education

Definitions

This book deals with the design method in engineering. Engineering, design, and a host of other expressions, must therefore be defined in order to clarify subsequent discussions. The following two definitions will be adopted:

(1) Engineering design is the use of scientific principles, technical information and imagination in the definition of a mechanical structure, machine or system to perform prespecified functions with the maximum economy and efficiency. 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 in service (FEILDEN, 1963).

(2) The engineer is in fact the means by which people are able to enjoy the fruits of science or invention, whether in building new projects, or in maintaining and keeping up to date what is already in existence. Each generation must learn that technical knowledge without a sense of mission and responsibility is wasted.

The wealth of a nation, and all that implies, depends in fact upon the efficient organization of its resources both natural and industrial as well as human. In this organization the engineer bears the chief responsibility. Any large engineering project must depend for its planning and successful completion on the closest possible co-operation and integration of many specialists (DUKE OF EDINBURGH, 1961).

In order to fulfil his duties adequately, the designing engineer needs certain types of knowledge and skill, which may be summarized under the headings: theory, manufacturing technology, working constraints and design method (see *Figure 3.2*). All engineers must have a working knowledge of these subjects (although the subjects are by no means in watertight compartments). The composition of their individual fund of knowledge and skill depends largely on the nature of their work, whether it be production, management, design or even research. It also depends on the industry and the type and size of organization in which they work.

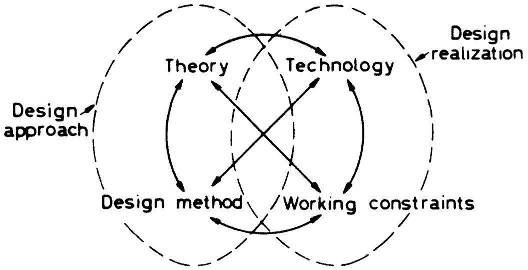


Figure 3.2. Designer's knowledge

Theory

In this context, theory consists of the fund of knowledge of mathematics and its application to kinematics, dynamics and statics of mechanisms, fluids (compressible and non-compressible), heat, light, electricity, strengths of materials, statistics, *etc.* It must include a thorough knowledge of the assumptions on which the theoretical investigations are based (usually stark simplifications in order to make the phenomena amenable to mathematical treatment) and therefore also their limitations and deviations from the actual phenomena described by their mathematical formulations.

Manufacturing Technology

All engineering artefacts must be manufactured, and invariably by persons not connected with design work. This means that the engineer must have a reasonable knowledge of present-day manufacturing technology (although the designer can usually call on the production engineer for guidance and information). This must comprise a knowledge of methods of forming and of joining metals, plastics, ceramics, glasses, semiconductors, *etc.* and the properties of these materials during manufacture and service use; the methods of manufacture available or in development, both universally and within the engineer's own organization; and their economic use.

Design Method

This is intended to imply that general approach to a problem which is likely to lead to a successful solution. It must be backed by a certain amount of imagination and intuition, and a more or less systematic investigation of the problem including the use of helpful techniques or 'tricks of the trade'. The general pattern in engineering design consists of preparation (gathering information, *etc.*), incubation, verification and finally communication. Recent investigations show a marked similarity in design method between the pure artistic (such as sculpture), the functional artistic (furniture, industrial design, *etc.*), and the engineering fields. The differences are found mainly in the use of theory, the application of manufacturing technology and the other working constraints which render design progressively more difficult from pure arts to engineering.

Working Constraints

Although these could well include theory and manufacturing technology they are derived from economics (cost and value), aesthetics, the production organization, available space and time, and the type of goods in demand (capital, consumer durable, consumer expendable, *etc.*).

Type of Work

A design engineer may work as an individual, as the leader of a design team, or as a member of the team (together with other design engineers), and this will have some influence on the composition of the above factors, in particular the design method. Their balance will also be affected by the type of work on which the design engineer is employed, whether it is components, assemblies, system elements, or complete systems. For the purpose of this chapter these artefacts may be defined as follows (these definitions cannot possibly be rigid; there is a great amount of overlap between these fields and vast differences between industries). *Components* are individual pieces of material, usually with the properties of 'size', 'mass' and 'strength' only. *Assemblies* are collections of components, with properties derived from the components, but with additional properties stemming from the arrangement of components, such as 'speed', 'power', 'ratio'. *System elements* are usually assemblies of components, but they are destined to function as a part of a system, not as an independent piece of equipment. Their properties are usually described by 'transfer functions'. *Systems* are collections of such elements, interconnected to achieve the desired properties, but working in an environment that can cause disturbances (noise) in the system by influencing elements or their connections. Systems may be classed as flow systems (the flowing medium may be power, information, chemicals, *etc.*) with one set of inputs and one set of outputs, the transfer taking place in a set of common elements; or as associative systems, where two or more separate sets of elements working on separate inputs and producing separate outputs are required for the total function of the equipment (for instance a motor car with its power transmission, its electrical system, its braking system, *etc.*). The concept of the system implies a more mathematical approach and a consideration of a full loop of responses but it has been broadened to cover most engineering artefacts, including the human being as a functional part of the artefact.

A crankshaft, a resistor, or a filter packing could be classed as a component (the resistor, as an electrical component, is probably an assembly of a number of mechanical components including an insulator, wire and terminals). An assembly would be a heat exchanger, a slider crank mechanism, or a valve voltmeter. A hydraulic pump, or an electric motor could well be a system element, working as part of a machine-tool (a system closed by a feedback loop including a human operator) or a mechanical analogue computer (including various mechanical feedback loops). Transport within a country can conveniently be regarded as a system, with an individual motor car or a piece of motorway as an element in it, and a mathematical description requiring the use of statistics to give it general validity.

The Design Process

Following the definition of engineering design given above, a series of steps may be stated that constitute the design process. In any given design sequence for a particular piece of equipment some of these steps may be omitted or transposed in order, depending on the general circumstances and the type of goods to be designed, but this statement should cover most eventualities.

Sponsor's Requirements

The design process invariably starts from a statement in broad terms of the sponsor's requirements. This may come directly from a customer, as in the case of most capital equipment; from directors or the sales department in the consumer durable field; from an inventor who recognizes an unfulfilled need (either outside or within the organization, this may be a designer, a production engineer, a machine operator, an inspector, or even an innocent bystander); or from a customer feedback of deficiencies in, or new requirements arising from, existing equipment.

Analysis of Customer's Requirements

A full analysis of the customer's requirements is necessary to determine the true needs*, the desired function, and the conditions of environment, time, operation modes, *etc.*, under which the required equipment must function. This will also suggest where further information is required, either from the sponsor, from existing literature, or from research ('pure' or 'applied' experimental work).

Sifting

All this information must be taken through a sifting process, to determine the essential functions, the disturbing or restricting factors, and the less important factors that need to be kept in mind although they do not determine the design itself.

Feasibility Study

A feasibility study is frequently useful at this stage. Feasibility can never be proved, but violations of the basic laws of physics can prove that a solution to the problem as it stands is not feasible. The designer is concerned here with feasibility – testing the sponsor's problem – not with the testing of any suggested solution to it. The result of this study may well be a set of *evaluation criteria*, against which the performance of a suggested solution can be tested. It may also result in necessary *alterations to the sponsor's specification* to render his problem more amenable to a successful solution.

Sponsor's Approval

The sequence up to this point should result in a restatement of the sponsor's requirements, in new wording, considering all possible influences, and showing how well and completely his requirements have been understood. The sponsor's approval should be obtained for this statement, and for any subsequent changes that may prove necessary.

Problem-solving

The next step in the design sequence, is a cyclic process consisting of an analysis of the immediate problem, the suggestion of possible solutions (by searching for existing solutions or by true innovation), the evaluation of these solutions (by experience, prior art, mathematics or experiment), modification where necessary, and selection of the most promising of them. This process must conclude with a complete *specification of the hardware*, usually in the form of drawings with due consideration for its spatial arrangement, the proposed economic methods of manufacture, and where applicable also the aesthetics of the solution.

Production Organization

From here on the need for a production organization becomes evident. This must include management functions, a marketing branch and an economic guidance division, as well as the actual production, inspection, storage and testing facility. Usually it will take the form of a commercial-*cum*-industrial undertaking, but other forms are possible especially in the civil service, military and educational fields. The production organization is used by the designer to obtain the specified hardware, initially as a *prototype* for the whole or a small part of the system, in order to test (prove its function) and develop it (improve its function at least up to the required performance). The *production models* must also run through a series of tests, which are usually used for quality control purposes.

Marketing

The marketing branch now takes over, the designer only receiving notice of customer complaints and service faults, which help to increase his experience.

All this may sound rather idealistic, but most of these steps can be found in any engineering design sequence. The steps will not be of equal length or of equal difficulty: some may be taken over by other functions

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*** This is not necessarily what the sponsor says he requires, but the reason why he says that he requires this.**

within the industrial organization, some will be performed by individuals, and others by teams. Frequently a design sequence will not be a simple run-through, it will exhibit *backward overlap*, namely a return to previous stages as new information becomes available. A 'forward overlap' should in general be avoided: it usually involves jumping to conclusions, which may prove expensive.

Design Methodology – General Remarks

In recent years some attempts have been made to recognize and rationalize the design approach, and set up a universal and systematic design method. All the methodologies so far proposed fit into the design sequence outlined above, but each uses different techniques to reach one or more solutions to the sponsor's problem. Some methodologies cover the whole of the design sequence, others concentrate on important parts of it and may be fitted into other methodologies to improve their probability of aiding the solution of engineering problems.

The author has made a study of methodologies for the purpose of a course in Mechanical Engineering Design (EDER, 1964; EDER and GOSLING, 1965). The summaries presented here are his opinions on the uses of the various techniques and methodologies, with all due respects and thanks to the originators.

Although the borders are by no means precise, the six methodologies discussed in the following section are *(1)* experience, *(2)* modification and running redesign, *(3)* check-lists, *(4)* design trees, *(5)* the fully systematic method, and *(6)* the system search methods.

Some authorities claim that design can only be effectively performed 'by experience'. This begs the question of which type of experience is necessary, since there seem to be two basic types, the experience of the design approach and the experience of design realization. The fund of knowledge required for each type is outlined in *Figure 3.2.*

Experience of design approach can only be obtained by working through a design process on a number of engineering problems; but progress towards this experience can be fostered by guidance through heuristics (aids to problem-solving). This latter is the true purpose of design methodologies in the teaching of engineering. Two recent conferences have discussed various aspects of this: the proceedings edited by JONES and THORNLEY (1963) and by BOOKER (1964). The imagination needed to bring the design process to a successful and economic conclusion can be fostered by appropriate personal contact (the master–apprentice relationship). As yet there are no hard-and-fast guiding principles about 'best ways', but investigations on creativity are in progress in the USA and Great Britain among others. One result was a symposium held at Birmingham in July, 1964.

Experience of design realization is defined here as the experience needed to specify hardware in such a way that it can be produced economically in the existing (or slightly extended) production organization. This can only be obtained by work within an industrial organization, by making proposals for hardware and discussing these with the production and economic engineering staff. It requires an up-to-date knowledge of production technology and of the properties of existing materials, and a flexible mind capable of learning from errors (including those committed by other people).

Formal design methodologies *(3)* – *(6)* act as a framework for guiding the designer's thoughts. They are no substitute for creative thinking, but they can help to spark off the intuitive processes. They can also free the mind of the designer to some extent by relieving him of the constant worry of remembering all that has occurred before, especially the reasons for certain decisions. In addition, it becomes easier to follow two or more possible solutions until the superiority of one becomes obvious when they are compared by objective criteria of assessment. These methodologies also appear to help the designer by allowing him to find more solutions to simple sub-problems, and then eliminate unsuitable combinations, rather than think all the time about the main problem to the detriment of detail.

Design Methodologies

Experience

This involves 'throwing the future designer in at the deep end'. The budding designer either learns his own methodology, or sinks in the process. A good master (one who is not only a good designer, but also a good practical psychologist) can assist in acquiring this methodology. It is probably true that eventually every designer who works alone will fall into this category, he will use the other methodologies (or only their heuristic techniques) subconsciously. The mainstay of this design methodology is 'cut-and-try', empiricism, trial and error. It stays in the mind: only the occasional sketches, the layouts, the calculations, *etc.*, show that there is work in progress. The reasons behind a design decision rarely reach paper, and are therefore difficult to follow; this may be a severe disadvantage in cases of absence of the original designer, or of the discovery of a major error in the principles of the design.

Modification

Improvements in an existing piece of apparatus are frequently performed in this way. It involves studying reports on the performance of the existing apparatus, particularly of its short-comings, and altering the design to avoid these faults. If this is done with an inadequate study of the original design, such modifications can aggravate other faults. Long-term improvements in mass-produced products are usually attributed to this methodology, but innovations (radical departure from existing principles of operation) rarely result from its use. An attitude of 'design-and-modify' can prove very expensive in the early development of a new product, especially if the design has not been fully considered. Such running redesign rarely leads to a pleasing and functional piece of equipment, but to one containing many redundant parts that were included to treat a symptom when the real cause was overlooked.

Check-lists

It is possible to set up a list of influencing factors for each step of the design process outlined earlier. These lists could conceivably cover the requirements of all industries, and the individual designer can select the ones relevant to his problem. Such an approach helps the designer to remember and complete every stage of the design process, watch his progress, and put his thoughts and decisions on paper, in the opening stages in words, later as sketches and layout drawings supported by words and calculations. Great care is required to make the reasons for any decision clear, not only to the designer himself (for reference at a later date) but also to any other person who may have cause to refer to them, such as development engineers.

A large number of such check-lists are presented by MATOUSEK (1963) and a few others are published in Eder and Gosling. Matousek and ALGER and HAYS (1964) give similar techniques for evaluating possible solutions, based on a suitable check-list. Each solution is graded under the heading of a number of factors on the check-list into, say, five categories of quality or compliance: number one as the lowest, five as the best possible. Each factor is given a weighting to show its relative importance among all other factors (*e.g.* whole numbers 1 – 10). The grading number G is multiplied by the weighting number W, and the resulting products are added for each solution. The solution with the highest rating may look the most promising, but the next one or two should not be ignored. An example of such an evaluation is shown in *Table 3.1*

Design Trees

A design problem may be broken down into smaller problems, each of which may again be broken down, until finally each sub-problem

Table 3.1

General purpose domestic suction cleaning machine		Solution A Hand-held unit		Solution B Cylinder with paper dust-bag		Solution C Globe model with cyclone		Solution D 'Slipper' model with handle	
Factor	Weight	Grade	G x W	Grade	G x W	Grade	G x W	Grade	G x W
Handling (floor)	10	3	30	4	40	4	40	5	50
Emptying	8	2	16	4	32	3	24	3	24
Handling (movement)	5	5	25	5	25	4	20	4	20
Storage size	4	5	20	4	16	3	12	4	16
Versatility	5	1	5	5	25	4	20	4	20
Suction power	4	2	8	4	16	5	20	5	20
Particle size range	1	2	2	4	4	4	4	4	3
Fitting accessories	2	2	4	5	10	5	10	4	8
Handling (accessories)	8	1	8	5	40	5	40	4	36
Appearance	2	3	6	4	8	4	8	3	6
Sum	245 max.		124		216		198		203

has a simple solution. Combination of such solutions should yield a number of solutions to the design problem. This form of approach is illustrated in *Figure 3·3* and is amenable to search techniques using an electronic digital computer, as suggested by NEWELL and SIMON (1964). Such a programme would be a vast undertaking yielding many solutions which are not feasible, but some heuristic instructions may be entered to cut down the amount of work, and therefore time, spent. Only few situations are amenable to this treatment, because the sub-problems are difficult to foresee unless the problem has well-defined rules like a game.

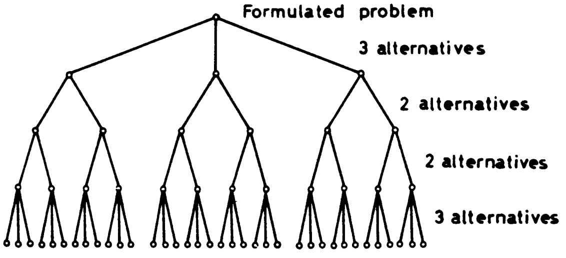


Figure 3.3. Game tree

The alternative suggested by MARPLES (1961) is to start from a statement of the main problem, suggest principles along which this problem may be solved, and find the sub-problems that must be solved before a solution to the main problem is possible. This involves a cyclic process of analysis of the problem, theorizing solutions, delineating these solutions, and modifying them (which again involves analysis, theorizing, delineating, *etc.*); this constitutes the ATDM cycle proposed by WALLACE (1952). The design sequence could well be plotted as in *Figure 3.4* where a vertical line denotes a problem, a slanting line denotes a solution. Any problem or solution may be picked out by means of the series of letters and numbers required to reach it from the origin (such as *a2b1b*), and this permits easy cross-referencing of notes, layouts, *etc.*

Ideally, a short statement of each problem and solution should also appear on this gradually growing design tree, with estimates of the difficulty of solving a problem, and availability of solutions. A good knowledge of precedent solutions (BOOKER, 1963) to similar problems or sub-problems is very helpful, especially if these solutions appeared in a different technology. Of course, all precedent solutions to the main problem, for example the competitor's model, should also appear on the design tree. A solution to the main problem exists when all problems thrown up by any one alternative solution have been solved (see bold lines in the diagram), and these solutions do not throw up any further problems. Work on any one branch of the design tree may, of course, be interrupted if other solutions are preferred. This technique can result in novel solutions if it is intelligently used by a lone designer, by a designer in charge of a team of specialists, or by a small team of designers. In the last case the documentation must be good to avoid unnecessary duplication of work.

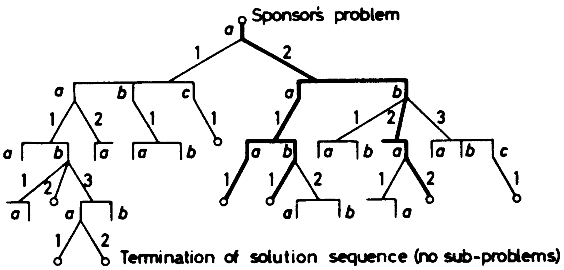


Figure 3.4. Design tree

Fully Systematic Method

As already stated, a certain amount of backward overlap during the design process is inevitable. This methodology, reported by Jones and Thornley attempts to cut overlap to a bare minimum by separating each stage of the design process and using various data processing techniques as described below to provide as complete a coverage of each stage as possible. The methodology is most useful for team work on large problem complexes, although many of the techniques may be used by individuals to great advantage, especially in connection with the formal procedures suggested by MATCHETT (1963) and illustrated later in this book. It is also usefully supplemented by heuristic questions and hints listed by GREGORY (1963). It is claimed that the use of this method can lead to design innovation on scanty evidence and in situations where experience is lacking, such as in new technologies, by bringing the design process consciously and (almost) completely outside the mind.

In the *analysis* (or preparation) stage the designer (or the team) sets up a *list of factors:* statements that have relevance to the problem in hand or to its solution. This should include considerations of the basic functions to be fulfilled, the capability and limitations of the production organization, the customer, the user, the environment and laws and standards; the life of the artefact (from the sponsor's problem, through design and manufacture, via transport, maintenance, storage, installation and use, to the scrap heap); the probable criterion of 'life ended' (end of useful life by failure in service, by completion of the required duty, or by obsolescence), *etc.* It is important to ensure a complete ban on criticism, to include all ideas even if they sound impracticable, and to allow duplication. Useful aids to this step are 'brainstorming' which includes looking deeper than the external features and for common features, and the use of the work study questions (what, why, when, where, who or which, and how; asking after the needs, justification, time, location, available or employed resources, and method). Each factor should be numbered in order of appearance and should consist of a single statement. Composite statements must be split up before the next step.

To reduce this information to workable proportions, these factors must be classified into a set of *categories*. Any factor that contains a suggestion for the solution of a sub-problem (a partial solution) should start a new category. The primary needs of the sponsor (if these are not solved, the fulfilment of other needs is pointless) should, of course, suggest the first category, or categories. be listed separately, and checked to see if there are any obvious omissions.

At this point it may be useful to place the categories in an *order of importance*, using a weighting chart (see *Figure 3.6*). If the category in the horizontal line is considered more important than the one in the vertical column, place a cross in that space, and a reference dot in the 'converse' space. The category with the lowest sum (category III with no crosses) is the most important, the placing of categories with equal sums is decided by the position of the crosses (*e.g.* VII more important than IV).

Sponsor's problem General purpose domestic suction c							ine	
No	*Factor content*	I *Housing*	II *Nozzles*	III *Power drive*	IV *Dust extraction*	*Ac*	*tic*	*Design File*
1	Easy to move around	X						o
2	Stable	X						o
3	Positive dust collection		X					o
4	Use domestic power			X				o
5	Get into small gaps		X					o
6	Damage delicate fabric ?			X				o
7	Dust catching in m/c				X			o
8	Suck up large bits				X			
9	Reach ceiling					X		
10	M/c easy to clean				X			
11	Electrical safety			X				o
12	Clean wood mouldings		X					o
					X			

Figure 3.5. Factor classification chart

Category		I	II	III	IV	V	VI	VII	VIII	*Order*
Housing	I		X	·	·	X	X	·	X	4
Nozzles	II	·		·	·	X	X	X	X	5
Power drive	III	X	X		X	X	X	X	X	1
Dust extraction	IV	X	X	·		X	X	·	X	3
Accessories	V	·	·	·	·		X	·	·	7
Tube extension	VI	·	·	·	·	·		·	·	8
Human	VII	X	·	·	X	X	X		X	2
Aesthetic	VIII	·	·	·	·	X	X	·		6
Sum		3	3	0	2	6	7	2	5	

X = Horizontal category more important than vertical category

Figure 3.6. Category weighting chart

Any suggestions of solutions should at this stage be filed for future reference in a *design file*. Each factor should be placed in one category only (if necessary, change the title and scope of the categories). A form as shown in *Figure 3.5* may be used. Having found suitable categories, the factors in each should

Each category will inevitably influence some others, and this should be investigated with an *interaction matrix* (*Figure 3.7*). In each case the nature or lack of the interaction between two categories should be questioned (another use for the work study routine), and the results noted. This process can reveal further factors that were overlooked in previous steps, especially if the lists of factors in each category are studied carefully. This matrix may be transformed into a straightened net by the process shown in *Figure 3.8* (each line denotes an interaction). Weak interactions between groups of categories may suggest splitting the problem into two or more parts.

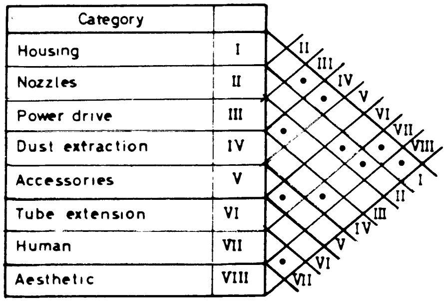
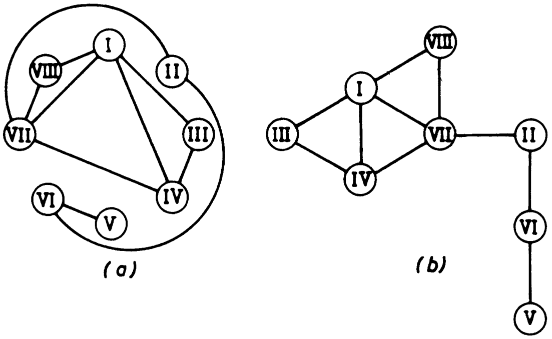


Figure 3.7. Interaction matrix



(a) *(b)*

Figure 3.8. Interaction nets

The interactions noted above must now be transformed into *performance specifications*, at least one such p-spec for each interaction. The p-spec must be worded to define performance, not a design requirement (*e.g.* meter to be visible from operator seat, *not* meter to be 1·6 m from ground level), and include permissible limits of performance. Complete separation of problem and solution can only be achieved if the p-specs contain no reference to shape, materials or design. The completed list of p-specs is a processed form of the sponsor's needs, including all other data that may be required for solving problems, and criteria for assessing the solution. The sponsor should approve (or modify) this specification before the next stage of the proceedings, to ensure that the right problem is being solved and an acceptable interpretation of the sponsor's requirements has been reached.

Conception (incubation) of solutions starts by solving each p-spec independently, in words and sketches finding as many solutions as possible and listing them in a 'morphological chart' after NORRIS (1963) (*Figure 3.9*). This is aided by such devices as listed by Gregory (1963) and JONES (1963): playing with words and concepts, studying precedent solutions, looking up the design file (started during factor classification), *etc.* The designer should note whether any p-spec or partial solution requires research, consultation of a specialist, a component test programme, or particular attention in any other way. Partial solutions should contain statements of limits within which the overall solution would be acceptable.

The partial solutions to each p-spec must be tested for *compatibility* with one another, (the interaction matrix may be used, asking the work study questions). By deciding on an order of importance, plotting on a tree such as *Figure 3.3* with the most important p-spec first and the branches 'growing' only where partial solutions are found to be compatible, and from this producing a set of dimensional layout drawings, a number of alternative solutions to the main problem should be found.

The best overall solution to the sponsor's problem must be determined by *evaluation* (verification) of the solutions found by the above procedure. This should be done by using the evaluation criteria included in the p-specs;

by simulation with analogues (mathematical, models, mock-ups, layout drawings, experiments, computers, *etc.*); by using component matrices after QUIRK (1961); by submitting the solution to the judgment of an independent authority or team; or by trying to modify, simplify, or transfer functions, eliminate parts, include other parts, combine or standardize parts or functions, *etc.*

No.	*Interacting categories*	*P-spec*	*Solutions*				*Remarks*
1	I - VII	Housing to permit easy movement and stability	No action	Wheels	Skid	Air cushion	d-requires development
2	I - VIII	Housing of pleasing shape, to reduce noise	Line with sound-dead material	Break resonance	Make out of sound-dead material	No action	
3	I - III	Drive to function in all positions of housing	Sealed ball bearings	Oil-retaining bearings	Dry-lubricant bearings		Take thrust in both directions
4	II - VI	Nozzles easy to fit, with air-tight joints	Bayonet joint	Cone and socket (self-hold)	Cylinder joint seal + clip		
5	II - VII	Nozzles effective for all conditions, easy to use	Fixed geometry nozzles	Variable geometry nozzles			
6	II - VII	"	Rigid nozzle material	Flexible nozzle material	Brush nozzle		b- narrow nozzle only
7	III - IV	Drive must not obstruct dust extraction	Dust cont. before fan	Dust cont. after fan			b- care in passages, no dead spaces
8	V - VI	Accessories to fit onto tube extension	No action	Joints as for p-spec 4			
9	VII - VIII	M/c to permit easy emptying and servicing	Dust cont. outside housing	Dust cont. inside			

Figure 3.9. Solution chart

The chosen design solution can now be *communicated* to the production organization, together with a written report containing a summary of all assumptions and their effects on the design; a description of function under all anticipated conditions; model instructions for assembly, control and maintenance; expected behaviour; a model test programme; and a critique of the design which should be kept open to include all customer complaints as they come in.

System Search

The basic assumption here is that the elements are available: that they are either obtainable 'off the shelf', or that technology is (or will be before the element is actually needed) far enough advanced that they can be made. System search concerns itself with obtaining the required system properties by connecting the available elements in a suitable way, and thereby bridging the gap between the inputs and the outputs.

Initially this is done on paper using an abstract 'model', a throughput flow diagram (TFD), where each block has a function but little or no relation to a separate piece of hardware (a system element). The blocks of the TFD can then be combined, split, redistributed and augmented by 'matching elements' (abstract or real blocks required to match or transform the output of one element to the input of the following element), until each new block has an equivalent available element of hardware; this is the block schematic diagram (BSD). The resulting system must be checked by calculation and experiment, and modified if necessary to yield the required performance. It may now be possible to reshuffle the elements or the inputs and outputs to optimize it with respect to performance or cost (capital, running or overall cost). Experimental checks at this stage are done on a 'breadboard' arrangement (in the flat) without regard to the future spatial arrangement of the elements relative to one another. Only when a satisfactory functioning system has been set up does the designer consider spatial arrangements, the optimum means of physical interconnection, and the aesthetics and human operator (ergonomic) aspects of the new equipment. This is done either on paper (a layout drawing) or by means of solid models.

The methods used in the early stages, up to and including the BSD, have been abstracted into a systems engineering approach by GOODE and MACHOL (1957), HALL (1962) and GOSLING (1962). Briefly, three approaches are possible:

(1) If a similar system already exists (with the same inputs and outputs, or with analogous inputs and outputs), a BSD can be derived, a TFD abstracted, and a new BSD can be set up to yield the new system using different elements.

(2) If an almost similar system exists (with the same or analogous inputs or outputs, but with differing values for the other) the TFD may be subjected to 'perturbation' before the new BSD is derived. For this purpose, the properties of a block in the TFD are (arbitrarily) changed and the effects of this change are propagated downstream towards the output (or upstream, or even both) to determine the possible change; the change is then optimized until the required properties are obtained.

(3) If no similar system exists, then cascading a number of sub-systems or unit elements may yield the required system. Work proceeds either from one end, or from both, listing all possible steps in the form of a 'tree' (*Figure 3.10*) until one or more bridges that appear possible can be found. Alternatively, if an available system appears to fulfil the bulk of the function, the problem may be reduced to finding the bridging system at each end, as in *Figure 3.11*.

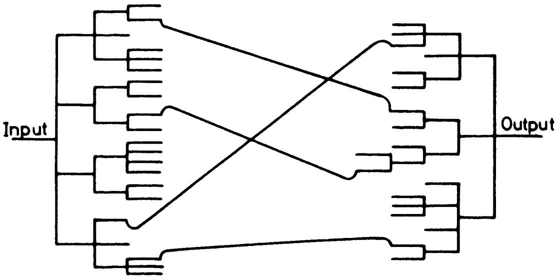


Figure 3.10. System search tree

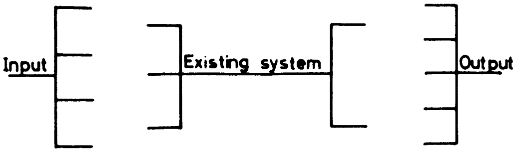


Figure 3.11. Double bridging

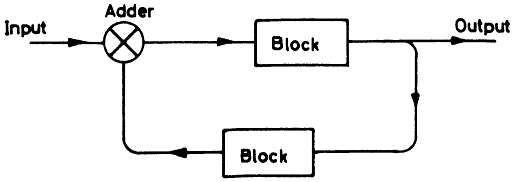


Figure 3.12. Feedback

It is important to note that most systems are not 'open' as *Figures 3.10* and *3.11* imply, but that they usually contain feedback: a portion of the output of the system or a small sub-system is suitably transformed and added into (fed back to) the input side (*Figure 3.12*). This can occur deliberately (to make the system dynamically stable, or to make it oscillate in a controlled fashion), or by accident as stray interference due to electromagnetic coupling, sonic vibrations, trapped matter (in boundary layers or in dead spaces behind baffles) *etc.*

The loop may even be 'closed' by a human being, watching the properties of an output (displayed by meters or signals) and creating a deliberate input by force or position of a lever, handwheel, pedal, pushbutton, *etc.*

This obviously is one of the main features of the interaction between man and machine. The system forms part of the environment for the human operator, and the human operator is an environment for the system. Each contributes properties in terms of practical possibilities, capacities, and patterns of failure. All design evolves and revolves around the human being, as creator, user, and master of engineering artefacts. Therefore the designer must constantly be aware of the needs and properties of his human environment, whilst applying technology, methodology and economics towards fulfilling those needs.

The interrelationships between specific technologies and varieties of design are considered in Chapter 33.

PART II

THE HUMAN PERSPECTIVE

Chapter 4

THE HUMAN PERSPECTIVE, THE DESIGN SITUATION AND ITS OPPORTUNITIES

S. A. Gregory

Introduction

To design is to plan for the fulfilment of human satisfaction. In Chapter 5, Mayall develops the idea of the spectrum of product – person relationships, of the variety of ways in which a product may affect the individual who uses it or consumes it. His argument is particularly expressed in terms of the relationship between capital equipment, such as machine-tools, and the operators.

The consumer is more than an operator of machines, although, in modem society, an increasing number of the satisfactions which are at his disposal come from mechanical equipment in and around the home.

Mayall sees the first approach to design as likely to be in terms of the immediate 'technical' solution. This holds true for either the simplest consumer products or sophisticated capital goods. For capital goods the technical function of the machine is important. For consumer goods, on the other hand, concem is with the function of the consumer.

Certain fundamental needs of the consumer may be expressed, and these are listed by Stobart in Chapter 6 as food, shelter, heat, light, and pleasure or recreation. MASLOW, (1954) approaches the matter in a different way. Some of these needs may be put in quantitative terms. A certain basic requirement of food exists for humans to grow, to work, and to live without obvious discomfort in specific atmospheric conditions. This is a requirement of physiological function and is related to age, to work, and to physical environment. To define the basic food need the other factors must be defined. Such definition is by no means easy nor, for that matter, is it likely to be productive except in time of siege or national catastrophe.

Some foods are preferred above others because of their taste, or their consistency, or their after-effects. Some, indeed, find favour because of their colour or shape, their social prestige, the advertising which has promoted them, or because they fulfil some deep-down urge or some traditional formula. Where men are no longer at starvation level, and sometimes even if they are below it, they express choices which cannot be traced directly back to simple physiological need.

In the examination of the needs for shelter, for example, definition is found to be even more difficult and imprecise. Shelter is related to food and clothing, to environment, particularly the weather and its changes, to the behaviour of animals and people in the vicinity, and to the materials available for building. Apart from such material features, the psychological demands of security and the level of aspiration must be considered, together with the complex of tradition and fashion; the social background and the skills and techniques available must also be examined. Such are the requirements for any detailed study of needs and wants.

The Marketing Approach

The study of opportunities for design, which means opportunities for business action or for the exercise of public welfare agencies, is essentially that of marketing, as it is expressed today. The marketing approach, as discussed by DRUCKER (1964) and others, is the orientation of organizational resources to the satisfaction of the consumer. In this the first task is to establish the market opportunities which exist for the organization.

The study of opportunities does not initially demand the full range of skills now made available by the human sciences. What is usually needed is an examination of commercial data on sizes of population, population growth rates, national incomes, the breakdown of consumer expenditure, and so on. For basic consumer goods, raw materials, and capital equipment it is usually possible to find crude overall figures by one means or another.

Methods of arriving at data of this kind are discussed in some detail by STACEY and WILSON (1963); some other references with relevance to industrial products are provided by Turner in Chapter 27. The theory of needs research is dealt with in depth by HALL (1962). In a chapter of his book he examines the mathematical relationships which are generally relevant, even if the data are absent. The provision of data regarding the present circumstances, in situations where specific information on the particular market is lacking, has been discussed by SALOMON and BROWN (1964). The difficulties, both technical and personal, of long-range forecasting, have been picturesquely described by MUMFORD (1963).

These activities may be seen as part of a larger operation, of marketing as a whole. Most of the thinking about marketing has been in terms of consumer products. The general problems and requirements of marketing have recently been covered by RODGER (1965) and the requirements of the introduction of a new product have been reviewed by COOKLIN (1964). For engineers and people concerned with industrial products the field has been clarified by the new book *The Marketing of Industrial Products* edited by WILSON. For a particular occasion a product profile may be set up similar to the proposal of HARRIS (1961) and WARD (1965).

People who have a close contact with the needs of the market see clearly that market factors are design factors: the points which need to be made clear to a potential customer, in order that he may acquire the product with the greatest potentiality for satisfaction, are those points which have been carefully dwelt upon by the designer. They are not, of course, the only points which a designer has to worry about. He has to consider technical possibilities, the resources available to his organization, and so on. Somewhere too consideration has to be given to the future, both of the market and of the organization, and this has to be built into current products. The strategic approach is dealt with by WILLIAMS and FINLAYSON (1963) and by DE VRIES (1964).

The Rise of the 'Soft' Sciences

Although much may be done by fairly simple procedures to improve marketing, eventually a limit is reached when it becomes necessary to employ some more sophisticated approaches. Usually some application of economics is the first step. The behaviour of the market and of the organization are defined in economic terms, and the product is specified and analysed in economic terms. Similarly the sum of satisfactions is set out in economic terms.

Analysis of practical situations shows that a simple economic model is not satisfactory for a company, as in the recent study by WILLIAMS and SCOTT (1965). Although there has not yet been an adequate study of design practice, it may be reasonably supposed that design decisions are the outcome of some operation more complex than technical and economic considerations. The customer and consumer requires much more from his purchase than adequate technical performance at a low price. It is to the study of this point that more work is being devoted by experts in various branches of the human sciences.

What does the consumer want? This itself is a problem of considerable technical difficulty. What makes the consumer take his decision? From simple description of need more information must be dug. The psychologist is required to reveal motivation, even the social anthropologist to lay bare the role of the product.

Nor is this a problem just for consumer goods. The pioneering work of Peplow (Chapter 9) shows how even with industrial equipment there may be substantial psychological factors at work to influence acceptance. His contribution links up remarkably with the earlier work of ROGERS (1962) which deals with the diffusion of new techniques, largely those used in agriculture. It is by no means without significance that, as yet, there is no universally satisfactory or accepted theory of economic development. Growth may be described and projected but not readily explained.

But it must not be taken that shortage of this kind of fundamental theory leaves the designer without resources and possibilities of action. It is a good rule to provide in a design those functions which are essential and to do this at the lowest cost. It is a further good rule to seek out information from those able to influence decisions. But even with these rules success is by no means assured. With novel technical products, such as electronic equipment, the information that may be obtained is likely to be as good as that given 'by putting probes through the side of a cocoa-tin to find out what is inside'. Contact may never be made.

Aesthetics and Symbolic Value

Each specialization in design has its own magic and meaning. Instead of treating the range of skills as a basis for dealing with the continuum involved in each problem, people tend to concentrate upon a single approach, an approach which depends upon their primary training or inclination. Between the most extreme of these approaches, the strictly technical and the finely aesthetic, there tends to be a gap. Most of the aspects of Mayall's spectrum can be seen and procedures set up for their ascertainment, but the aesthetic and symbolic largely evade satisfactory quantitative treatment.

This is not a matter which is limited by simple items of consumer demand. Large complexes of structure such as town centres, new housing estates, and major industrial sites lay claim to attention. What can be found out from the students of aesthetics to help bridge the gap which lies between the purely technical solution of the problems of function and the ill-defined attempts at the attainment of style and form?

Philosophers, such as CARRITT (who gives a compact list of references), have little to offer other than a critical approach, and would direct attention to physiology, psychology, anthropology, sociology. For many years, artists have known of particular geometrical shapes with the ability to provide a minimum of satisfaction, or at least an absence of tension (see Newman in Chapter 13). Such is the relationship given by the 'golden section'. Artists and others have developed structures of theory around the subject and many of the shapes recorded in nature by THOMPSON (1917) find favour. More to the point has been psychological investigation and much of this is conveniently brought together by VALENTINE (1962). But this kind of psychological work is only able, through experiment, to deal with relatively simple phenomena. Those aspects of perception now being studied by the ergonomists to help in their appreciation of man – machine interaction, concern the delivery of data to the human brain, a complicated piece of equipment which is able to influence the choice of things perceived and the way in which they may be interpreted. GARNER and colleagues (1963, 1964) are approaching aesthetics through experiments based on information theory.

The practical consequences in art are well brought out by GOMBRICH (1960) who brings to his discussion considerable sophistication regarding the views of psychology. The attempt to bring together modern views of psychology and the nature of architecture has been made by NORBERG-SCHULZ (1963). This is a topic in which discussion may run far from practical considerations. Architects, of all designers, seem to run the most risk of an inadequate definition of objective. PERLMUTTER (1965) shows the problem in other ways.

Conclusion

A person's first task as a designer is to find opportunity where need may be satisfied by the use of his particular skills. This need will be based largely upon what he recognizes as economic and social considerations, and his decisions in design, beyond technical feasibility, will be determined by them. But he has to recognize the important part played by perception and the way in which its function and extent varies according to the product. He has to put into his design just the right amount of 'perception engineering'. He must, in the words of Mary Follett (as reproduced by METCALF, 1941) find and obey the logic of the situation.

Chapter 5

DESIGN AND HUMAN SATISFACTION

W. H. Mayall

> 'An engineer is one who directs the great sources of power in nature for the use and convenience of men.'
>
> Thomas Tredgold

Introduction

By whichever route most engineers reach the point of designing products for human use and convenience, they acquire no more understanding of people and society than their own personal experiences and powers of observation permit. With respect to engineering designers, as indeed to other types of designer, both of these abilities may be limited. For the engineering designer the limitation may be especially severe. Technological development has forced him to concentrate upon increasingly complex technical problems. Consequently his professional education is heavily biased towards techniques. Indeed, for many engineers the design of engineering products is largely interpreted as a process of producing technical solutions. This task is not, of course, to be underestimated. It would be entirely wrong to suggest that engineers should gain a greater understanding of people and society at the expense of acquiring technical expertise. Such expertise is needed to an increasing extent. But if it is to be properly utilized then a fuller knowledge of the users of more advanced products and how these products will affect society becomes more necessary.

There are several reasons why this need must be recognized. First, the comparatively rapid development of so many types of product since the beginning of the nineteenth century has, by and large, created a seller's market. Especially with engineer-based consumer products such as automobiles, refrigerators and so on, people have been only too anxious to acquire them; and with little or no prior experience have not been able to discriminate between those which are suitable and those which may be unsatisfactory. Wider ownership of such products, increasing ownership experience, and the work of a variety of consumer-conscious organizations are changing this situation. Without formal instruction, a condition which might well change in educational patterns of the future, the buying public is slowly becoming more selective. In the so-called affluent societies the purchaser's ability to discriminate is clearly backed by a financial ability to do so. It can be argued that affluence encourages an appeal to comparatively slight or superficial needs. Thus a car may be bought for its colour rather than its technical specification, for its quality as a status symbol rather than its performance characteristics. Indeed, the problem of a highly affluent society may be the creation of needs which engineers, in particular, may regard as entirely ephemeral. But however slight these created wants may appear in the design of consumer products for such a society, they cannot be overlooked. Even a slight understanding of social history demonstrates that the affluent have always exercised their foibles in their choice of products; a very sound reason for being affluent.

Although the financial power to discriminate may be smaller in less affluent societies their ability to discriminate is growing, partly due to trading competition and partly because financial limitations demand selection of the best available products. Such discriminatory ability in these societies may relate more to the purchase of capital plant and equipment. Such products may be seen not simply as means to but emblems of social development and thus carry psychological overtones which a perceptive manufacturer should recognize.

While increasing powers of discrimination at most purchasing levels is perhaps the prime reason for making product design more than a matter of solving technical problems, a close second is the far greater investment required to design, develop, and tool-up for modern engineering products. For a new car the investment can run into several million pounds. A very small electronic unit recently examined, cost in the region of £60,000 to bring to a preliminary production condition. Obviously investments of this order are unwisely made if a thorough study of those for whom the product is intended is not undertaken. And although it is sometimes believed that the creation of wants by mass-advertising may carry a product through, as it were, it is doubtful if such 'created wants' will prevail unless they are related with current or projected social conditions and aspirations. Perhaps the most quoted example in this respect is the ill-fated Ford Edsel car. Wrongly believed to have failed because it was made by a company with an excessive zeal for market research, the Edsel failed because, although a market had been discerned (the rising executive class) the Ford company did not recognize that this class could not, on the whole, see the Edsel as an emblem of executive status. The Edsel affair makes the point that it is necessary for a manufacturer to recognize his own personality as well as the personalities of those he is intending to serve. The financial loss to the Ford company was in the order of £120 million. Yet the engineering was probably perfectly satisfactory in terms of the current state of the art.

Product investment costs are likely to continue to rise so long as products continue to become more complex in technological terms. Thus those who may be engaged in some of the most specialized technical tests might reflect that the cost of their own services must be regarded, in part, as a reason for paying more attention to those who will use their products.However refined their accomplishments and however large the costs they incur in product development their work could fail for purely 'human' reasons.

A third, and for some the principal, reason for recognizing human needs and attitudes is that a time might be rapidly approaching when, unless a greater sense of social responsibility is undertaken by manufacturing organizations, with active participation in social planning, society may suffer rather than benefit from technological development. The effect of the automobile is usually cited in this context, whether in terms of safety – the writer recently observed the effects of the stylized prow of one vehicle upon an elderly lady – or in relation to the points raised by the Buchanan report, for example. In one sense this report can be regarded as an attempt to correct foreseeable, indeed foreseen conditions. But correctives may take so long to apply that, bearing in mind changes due to other types of development, they could well be frustrated. A Luddite solution to this type of difficulty inevitably springs to mind, but this is neither desirable nor practical. Alternatively to impose some kind of dominating central control for what some people regard as a technological free-for-all would be unpalatable. The main task must surely be to recognize that products help to form social patterns; an aim must be to predict how these patterns will change with the introduction of new types of product. Thus the engineer must look beyond his own product and the people who will use it to other products and their relationships. In consequence, and as a creator, he must necessarily associate with other creators – architects, industrial designers, artists – if human satisfaction expressed in terms of social responsibility is to be fulfilled.

An Outline Approach to Human Needs in the Design Process

The growing interest in and partial appreciation of systematic thinking in the design process must be developed with a recognition of human needs. But it would be naive to suppose that systematic techniques can be devised which, in themselves, will produce what might be called human answers. There is the dangerous chance that this kind of thinking may develop very largely because designers can easily become formulae-bound. The formulae need not necessarily be mathematical in character. Styling formulae, in the sense of picking up and perpetuating a particular shape or configuration, are all too apparent in the more aesthetic areas of design for products. In dealing with human requirements it may be more profitable to consider how the designer can systematically ask the right questions rather than how he can by system obtain the right answers.

There are two reasons why this course is likely to be more profitable. First, a most important point about people is that they are human. They do not behave in the neat predictable manner of mechanisms. Their reactions to and ways of using a product in one set of circumstances may be entirely different from those in another set of circumstances. They differ in dimension, in physical and mental abilities, in culture, and in aims and aspirations. They can confound those who, with the best intentions, contrive to produce the 'logical' answer to their perceived needs. Thus a comparatively transitory style, say in the structure of a chair, may well influence them more than that the chair is satisfactory in ergonomic terms. A reduction of the degree of human skill required to manipulate a product may well cause resentment rather than receive acclaim, especially if this skill has been hard-won and confers distinction upon those who possess it. Such attitudes are not arguments for ignoring ergonomic factors but simply illustrations that designing for people involves more than current interpretation of ergonomics tends to recognize and, more fundamentally, evidence that people cannot be encapsulated by formulae. It will always be necessary to treat each product situation on its merits.

A second reason why questions are more important than answers lies in the nature of the design process. A fundamental characteristic of this process is that of making adjustments or compromises in order to achieve a so-called optimum overall solution. In the design of most products the 'optimum' is not necessarily a unique or ideal solution. It is determined by management policy, by available resources, and by the target dates, all of which vary from time to time. Thus answers to human aspects listed for one set of conditions may not be relevant in another set of conditions. Some engineering designers may be familiar with those who attempt to press a particular mathematical formula into service because it appears to approximate to some mechanical or structural design condition. They know that misleading information can frequently result from this tendency. Similar effects may occur if data on human behaviour are applied without questioning the overall person–product relationship.

Just as it would be naive to suppose that systematic techniques can in themselves produce 'human' answers, it would be presumptuous to believe that a kind of human questionnaire can be produced on virtually *a priori* grounds. Such a questionnaire must eventually come from continuing studies made by designers, human factor specialists, social scientists, and objective market researchers. Many aspects of person–product relationships remain unexplored while others may seem to have been veiled with a mysticism which one cannot but feel to be sustained purely for the personal profit of a variety of 'experts'. But while waiting upon more research into person–product relationships it would be reasonable to suggest a mode of thinking which, for engineers in particular, might help to extend their attitudes and provide a basis for asking questions. The mode of thinking suggested here is certainly not put forward as the only one which can help to encourage a wider appreciation of human needs. In fact it tends to overlook one important aspect of product design which will be considered later. But at least it may serve as a starting point for further investigations.

The Spectrum of Person – Product Relationships

For the engineer the core of the design task is always likely to be the achievement of a technical solution. Taking the colour spectrum as an analogy, the so-called technical factors involved in design could be regarded as a broad band at one end. These factors, basic performance characteristics, efficiency, life, suitability to ambient conditions, and so on, might be achieved in theory without reference to human characteristics. On occasions one suspects that this happens. However, the choice of technical solutions must depend upon whether they permit the product to be transported, installed, operated and maintained. Therefore recognition of human characteristics in terms of size and physical ability will usually be first for consideration. Satisfaction of anthropometric and physiological requirements could be regarded as forming the next band of colour along the spectrum, linked to technical aspects by equivalence in measurement, *i.e.* in terms of length, mass, time and energy.

Further along the spectrum the next distinguishable band could identify the psychological relationship between human and machine. For the engineer this relationship will have the greatest emphasis where it relates to operational aspects. In this regard he will, or should, be concerned with how operational information is presented to the human being, how this information is interpreted, and how control information is fed back to the machine. This aspect of product design cannot be considered without taking physiological characteristics into account. It seems reasonable, in consequence, to locate this as the next human aspect along the spectrum. But psychological considerations extend beyond those concerned with manipulatory or control activities. They broaden out to what are usually defined as aesthetic considerations. This is particularly the case with the majority of production machinery in so far as visual and tactile faculties are concerned. For example, reactions to form and colour on production machinery will usually be based, either consciously or unconsciously, upon whether they assist control requirements. Even where an ergonomic approach to the use of form and colour may be less important, it is reasonable to assert that aesthetic reactions can be classed as psychological. As long as there is an inadequate understanding of the constituent elements of an aesthetic reaction, it would be unwise to do more than tentatively suggest how such a reaction may be composed. A study of the aesthetic critiques tends to show that certain concepts, particularly the desire for unity and orderliness of form, can be related with some of the concepts propounded by the Gestalt psychologists. These concepts would appear to have universal relevance and, indeed, they can be utilized in determining machine-control layouts. Mainly for purposes of identification these concepts might be described as 'basic aesthetic factors'. However, they are certainly overlain by others which are less understood. It may be convenient to identify these other aspects by the word 'style'.

While a product's style is strongly conditioned by the materials and processes employed in its construction, the effect of the product in relation to its intended environment cannot be overlooked. If the aesthetic desire for unity is required in the product itself then it is reasonable to expect that it will be sought in relation to current standards in architecture and in the form of other products. It is important to recognize here that environmental influences upon product style may be conceptual rather than real. For example, one would not expect to design a nineteenth century appearance into a machine destined for a twentieth century factory. The machine, regarded as modern in concept, will usually be more acceptable if it bears a recognizable relationship with other modern products. Architecture has always had a strong influence upon other products.

Conceptual attitudes to products bring one to the end of the spectrum. Here a band can be identified which, while linked to so-called basic aesthetic concepts through environmental considerations, begins to relate with a variety of symbolic interpretations which people tend to place upon products. It is in this area that more needs to be known than is at the moment. For, though they come to the end of the spectrum of human satisfaction, symbolic interpretations can play a very large part in determining product sales. Their influence is certainly more noticeable in the character of consumer products but is not to be ignored in the field of capital plant and equipment. For example, some time ago a manufacturer redesigned a machine to save time on finishing cast housings. He calculated that it was cheaper to surround these housings with a sheet metal casing which would be cheaper to produce and finish. But while a number of purchasers readily accepted the change, since the manufacturer was able to cut the price, one potential purchaser rejected the product because he could not see that the machine was made of the 'good solid cast iron' he had always associated with machinery. Indeed he preferred a more expensive machine without difference in performance characteristics.

Conservatism in product acceptance and belief in social status acquired both in owning a particular type of product or by the nature of the product itself can vary considerably between different people and different social groups.

There are those for whom the symbolisms generated by many types of product are to be either derided or ignored. The fate of the Edsel car should be a salutary reminder that derision is an extremely risky pastime. Others may attempt to make ethical issues out of such influences, suggesting that 'education' would encourage people to see through what they may like to describe as sham values. But however these values are described they have existed, in their kind, throughout the history of human society. Much could be learned from a closer historical study of these aspects, for, up to the moment, very little objective analysis has been undertaken in relation to product 'images'.

Possibilities in Adoption of the Spectrum Analogy

By listing human requirements in a connected order stretching from meeting ergonomic requirements, through basic aesthetic needs, to the recognition of environmental influences, with symbolic meanings finally, a form of importance rating is automatically expressed. Thus in general, ergonomic needs should be regarded as having greater importance than style. The analogy stretched to include technical factors, helps designers to produce, if only very roughly, a graphic expression of the relative importance they are giving to the various design factors listed along the spectrum. In all design situations one would obviously expect technical requirements to have the greatest importance and a hypothetical 'importance rating' graph would always slope down towards the symbol end of the spectrum. But it is not too difficult to visualize different rates of slope for different types of product. For example, factors making up the style waveband are of more importance in consumer product design than in capital goods design.

Finally, if it is accepted that a logical connection can be made between the various factors making up the spectrum, then the analogy may help to serve as a preliminary model upon which more detailed studies of human needs and attitudes can be made. While hoping that these more detailed studies will be made, one may suggest that the analogy could form a preliminary guide for the designer, both in forming questions on human aspects and in seeking and assessing available information in relation to his design project.

Conclusion

The analogy suffers from one drawback in that it does not take account of the product's effect upon society. The concern is with the total effect of the product. To take an extreme case, an ergonomically and aesthetically satisfying flick-knife is no contribution to social betterment.

If they are to be seriously concerned with human satisfaction then engineers and designers in general need more than systematic techniques, analogies, or other devices, to help them extend their attitudes. Certainly, for great areas of the world, possession of the benefits brought about by science and engineering are, and will be for some time, a major aim. But it may be wrong to suppose that, because it has been so to the moment, technology will always be beneficial. It might be considered that a stage is being reached where consciousness of human values, in the very broadest sense, must play a more dominant role in the way that scientific and technical efforts are directed.

Chapter 6

INVENTION, DESIGN AND MARKET RESEARCH

A. F. Stobart

Introduction

Every man-made object was originally an invention in the mind of one or more people, followed by a design for its manufacture and, in due course, by the development of a market for the product. Inventions can occur without design and marketing; inventions and designs can take place without being marketed; but no marketing can be done unless invention and design have previously been carried out.

Market Research and Design

In modern civilization it is quite possible that a study of a particular set of human conditions, often known as the process of market research, can throw up the need for certain inventions and designs to take place, to fill gaps in the requirements, or the luxuries, of the civilization concerned. The court jeweller to a potentate of ancient time would take good care that his products were designed to be suitable for his master's taste or those of his female entourage. Equally since there is fashion in engineering, as in jewellery, the modern engineer frequently has, at least outwardly, to design his works to suit the taste of a particular client or his engineering entourage. In either case the result can be a very gaudy display of little intrinsic merit.

Market research for design, then, can be divided into two parts: *(a)* to discover what a market thinks it needs; *(b)* to discover what a market would ask for if it really knew its needs.

The second type of market research involves undertaking a considerable part of the design work for the market technical development before going out and studying the market itself. The success of the market development will depend as much on the design of the goods themselves and of the service by which they are supplied as the price at which they are offered. To quote Sir Arthur Bryant: 'The quality design of goods exported, and the integrity and despatch with which British traders met their customers' demand, gave prodigious dividends.'

This refers to 150 years ago. Can the same be said today?

Design for Markets

Leaving aside for the moment original invention, which is usually not connected with any immediate prospect of sale but is the result of necessity, curiosity, or urgent personal need, design can be said to be aimed at fulfilling a few basic human needs. These are: food, shelter, heat, light, transport, and pleasure or recreation.

One of the most fundamental features of modern civilization is its transport system, for men, ideas, and materials. It is proposed to discuss design in connection with transport. In the words of Kipling: 'Transportation is civilization, and only when perfect freedom of transport and all that it implies, is maintained in the world, can the world be said to be truly civilized.'

The British people, possibly more than any other race in human history, have been the repeated instigators of new methods of transport. In the early years of the medieval kings there was freedom of transport between one town in England and the next by whatever means were available, while Europe maintained its petty independent states, levying tolls on all travellers. England developed heavy transport, first by the exploitation of existing natural waterways. The development of railways, as a kind of overland canal, came later. Today, the oldest form of organized transport, by road, is being taken in hand after a lapse of nearly 2,000 years since the Romans first laid down the backbone of the present road system. In addition Britain has three different kinds of transport of more modern character: the transport of power by high-voltage electricity; the transport of gases, liquids, and occasionally solids, by pipeline; and the wide diversity of air transport.

How then does design influence transport? And how, indeed, does transport influence design? How do both have a bearing on the exploration of markets?

No market can be explored without transport, whether it is transport of knowledge or physical beings. Primitive man, faced with the problem of exploring another part of the forest, which was difficult to reach through the thick undergrowth, conceived the idea of sitting astride a log in a local river and floating downstream until an attractive beach opened up the possibility of a good set of living quarters. But logs were notoriously unstable. So, either by some process of extremely ingenious deduction, or more probably by the advent of a partially rotten and hence hollow log, primitive man achieved the idea of the dug-out canoe, the ancestor of all boats.

Herein lie the first two lessons of design: the study of the application for which a design is required, and the awareness that an already available commodity can, with modification, be used to fill the need. A great deal of design for various markets is the adaptation of existing ideas, or the extension of existing designs and inventions to some apparently unrelated field.

There are many examples of mankind feeling a need, studying the natural method of meeting that need, and then adapting these natural ideas to use. The development of aircraft came originally from the study of the flight of birds. The development of structures came from the growing of trees and then from using parts of the tree as the basis for man-made buildings. In some old structures there is, in fact, little pruning of the tree trunk before it is fitted into the building. Given the tree-like shape as important, sometimes other materials were formed into the same pattern. The round stone columns of ancient Greek and Roman temples obviously owe their ancestry to timber columns used for earlier buildings.

But the activities of mankind in invention, design, and marketing, or merchanting, as it was called, were very limited until transport was developed.

Transport of Ideas

No invention or design springs into life complete, as Athene from the head of Zeus. A long, often slow, process of meditation, trial and error, and calculation comes first. Mankind has done so much of this groundwork in the last fifty years, on so many subjects, that much of the initial thinking on any new development has probably been done, if one can find it. What are the barriers to the movement of ideas? There are many, among the commonest of which are:

(1) Language – The USA speaks American, not English.

(2) Prejudice – 'Can any good thing come out of Nazareth?'

(3) Lack of fundamental knowledge, or of its application – Iron is a chemical as well as a metal. A pipe is a fundamental structural shape, more economical for some applications than the sections commonly applied. Are either of these facts taken fully into consideration as often as they might be?

(4) Inadequate classification and poor information retrieval – The author once developed, in theory, a device for the

purification of chemicals by sublimation. A prototype was built which worked well, but further search uncovered two facts. Machines of this type were in commercial production in East Germany, and the principle and outlines of the process had been worked out by the company's chief chemist in 1925. A very glaring example of inadequate searching and poor intelligence.

The true inventor has none of these hindrances. True, he may have prejudices, but they are his own. He is often not accepted by society (the market) because of this, although his work is useful and may ultimately find wide application. A true inventor rarely does market research. The designer takes the fruits of the inventor and converts them to articles which conform to the prejudices and fashions of the market. This is the site of the first transport problem in ideas. How to get them from the long-haired to the short-haired sections of the organization?

Sometimes the market may dictate a requirement for which there is no complete answer and at this stage the inventor may be deliberately brought into the picture. This is more commonly known in industry as 'calling in the research department'. Market research has a big part to play in feedback to the designer of the present and future requirements of customers. This means that the market researcher must understand the designer, another problem in the transport of ideas. The designer in turn must be capable of sorting out the problems which can be solved from current knowledge, and those which require the expansion of knowledge. The designer has, himself, to do market research. He must, as a potential buyer, do research in the highly specialized market for ideas.

A cost–time factor comes in at this point. Many ideas are sold, or leased, such as licences for patent exploitation. It may be worthwhile to pay for an idea from someone else if one cannot be sure of devising a cheaper alternative in the time available. The evaluation required involves the total cost of the purchase or rent of the idea, against the total profit accruing from its use, compared with the same figures calculated for one's own developments. The profits available from a quick entry into the market may more than outweigh the extra cost of buying a process. To develop one's own process involves waiting and an expenditure which is as yet unknown, but it could produce greater profit in the long run than a purchased process.

Market research is vitally necessary at this stage of development, to assess the courses of action which are available for the projected design, the influence of the timing on the success or otherwise of the venture, and the level of profit which can be expected from the various courses of action. At least one firm of consulting engineers has gone into this field very thoroughly. Computer programmes are set up based on the detailed economics of all the known possible alternatives in a plant design. The programme is run until two or three of the most profitable combinations of processes and equipment are thrown up, in the context of given market conditions. These combinations then form the basis for a tender to a customer.

Design is, however, of little value, unless something is made and/or sold.

Transport of Materials

Trade is the transport of goods from seller to buyer, and the transport of money or other goods in return. Before the goods can be made materials must be transported to the factory to make them. The buyer is ultimately in charge of this function, but it is the custom for the seller to seek out the buyer, rather than the other way round. Market research comes into play to locate the buyer, study his needs and habits, and plan how to provide satisfaction for them. The barriers to the passage of goods from seller to buyer can thus be uncovered.

Apart from the most obvious, and partly man-made, barriers of freight and duty, there are two main obstacles to overcome. These are price and value. Price reflects the efficiency of the producing firm in keeping costs to a low enough level to allow a profitable sale to be made at an attractive price. Value is the cost of use to the buyer, and is, or should be, the result of successful co-operation between the market research and design teams. Market research can pinpoint what aspects would be of most value to the user: design teams have to try to incorporate them in the finished article without overstepping the allowable production cost.

Another aspect of value is that most of the input should come from the brain and as little as possible from materials. Great Britain is an island, dependent for much of its food and raw materials upon imports. Her only major exports, apart from a little coal and iron, derive from the ingenuity of the inventors, designers, and craftsmen who live in the island. Market research has a vital role to play in guiding the brain power into the most profitable outlets in world markets. Sometimes, indeed, there may be a market for the idea alone, in the form of a licence to manufacture.

An interesting result of the reduction of weight of a product, with an increase in 'brain content', is that the price per unit of weight should go up. This, in turn, will reduce the percentage increase in price which has to be charged to cover freight. Thus a more distant market may be tackled with this new commodity than is possible with a commodity with a low price-to-weight ratio.

Conclusion

Invention pays little heed to market research, although it may be initially fostered or encouraged thereby. But design, which is the basis of all industrial effort, should – indeed, must – be guided in detail by market research to achieve the objectives of all successful business, maximum profits with maximum customer satisfaction.

Chapter 7

ERGONOMICS AND DESIGN

B. Shackel

Introduction

The contribution initially invited from me was psychology and design, which should be a broad enough brief to satisfy any author. However, the theme of this book is design method, and to concentrate on applied psychology alone seems unjustifiably limited in this design method context. Neither the user nor the designer of a product or a production machine limits his actions or responses to the psychological plane. The human factors side of this field must be concerned also with anatomical, anthropometric and physiological aspects, as well as the sociological and other areas examined in other chapters. Therefore, to embrace these related biological sciences, I propose to discuss ergonomics and design.

Machine designers are mostly, and quite rightly, concerned to improve the mechanical, electrical and other performance aspects of their machines; they sometimes forget that what matters most is the efficiency and performance of the total system, of which their machine is a part. Often the machine is one element in the man–machine system, and what may be more important is how well the machine works *in conjunction with the operator* who has to use it day after day in his routine work. Now, there is nothing especially novel about emphasizing this need for a good fit between man and machine; but the difference with ergonomics is that it provides the methods for a systematic scientific approach to the problem.

Engineers, managers and administrators have to make the final decisions on the design, acceptance and establishment of equipment and plant, and these decisions obviously affect greatly the efficiency and welfare of the humans to be involved. Errors can be costly in both human and economic terms, but not all such errors are necessary, let alone inevitable. Research has already yielded much relevant knowledge; but in many situations the engineer or manager may still have to fall back on 'rule of thumb' or guesswork. To replace such a potentially costly basis for decisions by a systematic scientific approach is a prime aim of ergonomics. Moreover, the engineer or manager himself often can and should use the relevant research findings, provided he is competent and able to interpret them correctly; it is not essential, though often helpful, to have the consultant advice of an ergonomics specialist in order to adopt this scientific approach to the human factors aspect of modern technology*.

What is Ergonomics?

Ergonomics is defined as the study of the relation between man and his occupation, equipment and environment, and particularly the application of anatomical, physiological and psychological knowledge to the problems arising therefrom. This definition, and the field work, clearly can embrace both research and practical application.

Research is essential to increase the the knowledge available on the multitude of ways in which men behave, how they are

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* References for this Chapter appear in the special section on p. 342.

similar to and different from engineering components, and how they respond to and are influenced by their task and environment.

Aspects of practical application are discussed in the rest of this chapter, but the equal importance of research must not be forgotten because without it there is no new knowledge to be applied as new practical problems arise. In the study and treatment of practical situations, Ergonomics (or Human Engineering, or Human Factors – broadly equivalent names used in the USA) places major emphasis upon efficiency in the operation of the equipment as measured by the speed and accuracy of the human performance. Allied with efficiency are the safety and comfort of the operator. Because the aim is to optimize the man–machine and man–environment combinations by altering the machine and the environment, this aspect has also been termed 'fitting the work to the man'. Equally important, although often regarded as a separate subject from ergonomics, are the personnel factors such as selection, training, and adaptation to environmental and working conditions. These are studied both as part of ergonomics and as separate topics under the headings of Work Physiology and Occupational Psychology. From this knowledge people can be helped to alter themselves, within limits, to improve the man–machine partnership; this personnel aspect has also been termed 'fitting the man to the work'.

'Fitting the work to the man' and 'fitting the man to the work' are obviously also major aims of managers and engineers, but ergonomics has a real contribution to make because of the specialized knowledge available about human characteristics and performance from the relevant biological sciences.

How did Ergonomics Develop and Where is it Practised?

What is now called ergonomics had its beginning in Great Britain in the scientific study of human problems in ordnance factories during World War I. This kind of work continued under the Industrial Health Research Board between wars. World War II led to greater emphasis on not merely matching men to machines by selection and training, but also, much more than previously, to the designing of equipment so that its operation was within the capacities of most normal people. This fitting the job to the man increased considerably the collaboration of engineers in certain fields with the biological scientists. This collaboration, beginning primarily with military problems, because it is there particularly that operators are pushed to their limits, continued after the war and led to the formation in 1949 of the Ergonomics Research Society. Attention has since returned to the industrial field, and the joint approach has increasingly shown its value as an ally, according to circumstances, of design engineering, work study, industrial medicine and personnel management.

The field has already grown so far that it is impossible to count, for certain, the exact total of groups at work in the world. In Great Britain there are some fifteen academic or applied research groups, and at least four units sponsored by the Services for military problems. For training there are now courses available of at least one year's duration for postgraduate students at the Ergonomics Laboratory, Cranfield College of Aeronautics and at the Department of Ergonomics and Cybernetics, Loughborough College of Technology; undergraduate courses have recently begun at the latter. At the former, ergonomics lectures are also a routine part of the regular engineering courses.

On the industrial side, the British Iron and Steel Research Association, British European Airways and the Central Electricity Generating Board have small sections at work. Smith's Aviation Instruments, *Design Magazine*, Michael Farr (Design Integration) and ICI each have an ergonomics consultant on retainer. The British Transport Commission, the British Motor Corporation and British Railways

(Southern Region) have commissioned significant work. Each of the following major companies, British Aircraft Corporation, Pilkington Brothers, Richard Thomas and Baldwins, and Lyons, has one qualified staff member working on ergonomics matters. The staff at Philips have worked mainly on shop floor problems but are now developing design work as well, and EMI Electronics has, it is believed, the largest and oldest (11 years) group, with a permanent qualified staff of four, working almost entirely on design problems.

In the past, Tube Investments, AEI (Manchester), Vickers Research, GEC Atomic Power Division, and the Boot, Shoe and Allied Trades Research Association have employed ergonomics staff and significant work has been done. In the present, active interest in the field is being shown at least by the following: Machine Tool Industries Research Association, Motor Industries Research Association, English Electric Atomic Power Division, Pilkington's Glass, Heinz and United Steel. However, although there now is this growing interest and activity over quite a wide field, it must be admitted that the total of real work and qualified specialists in industry is still very small indeed in Great Britain.

In Europe, the type of work and the rate of development is similar, but on the whole it is more scattered and a little less advanced. In the USA, particularly under the impetus of military funds, development has been much more rapid. At least 130 industrial companies have organized human factors programmes with an average group staff of ten, and the Services-sponsored units and the academic research groups are similarly more numerous. It is difficult to learn what may be happening in the USSR, but from a literature survey, RONCO and SAWYER (1962) concluded that 'although only a few articles were found that have to do with the direct application of knowledge of man's psycho-physiological capacities to the design of machines, ... sufficient volume of pertinent material is being generated to merit systematic attention by human engineers'.

Which are the Relevant Biological Sciences?

The biological sciences, from which specialized knowledge is applied, are functional anatomy, anthropometry, work physiology and applied or experimental psychology.

Functional anatomy is concerned with the body framework, posture, and the use of muscles; it can, therefore, provide knowledge of the best ways in which force can be applied or objects lifted and also about the limits of joint movement. This knowledge is, of course, very important in the design of controls such as levers and foot pedals.

Anthropometry yields data on body sizes and dimensions, both for male and female, and thus can help with the optimum design of the height and size of working surfaces, the position of hand and foot controls, the shape and height of seating, and so on. It is very important but often forgotten, that when designing equipment for females, female dimensions should be used. For example, the usual height of an upright chair is 18 in., which has been shown to be too high for about 60 per cent of both the male and the female population (FLOYD and ROBERTS, 1958).

Work physiology covers the whole field of bodily activity, particularly with reference to many different types of environment. For instance, reasonable measurements for physical work can be made in terms of calorie consumption, and on the practical side, it is possible from this knowledge to calculate the organization of work and rest pauses to minimize fatigue, *etc.* LEHMANN (1958) has shown how 'hidden' rest pauses may often have to be taken during heavy work and how it is more efficient to organize official pauses realistically.

Psychology involves all areas of behaviour and performance, particularly the mental and emotional aspects. Two broad sections must be distinguished, personnel psychology and engineering psychology. Personnel psychology relates for instance to selection, training, motivation and job satisfaction, whereas engineering psychology is concerned with perception, decision-making, and particularly such aspects as how an operator receives and processes 'information'. From this one can estimate, for instance, the rate at which the operator can be given information by a system and act upon it, what delays and errors may result, and how best to design the input and output equipment leading to and from him. CONRAD (1960), in describing some of his research related to post office telephone and letter-sorting problems, illustrates well this part of applied psychology.

It should also be emphasized how workers in ergonomics are aware of the future problems likely to arise from advances in technology. As long ago as 1955, MACKWORTH discussed the relevance of research then to the problems expected when automation came; and with automation still hardly arrived WELFORD (1960) could survey the aspects of ergonomics likely to bear on the design of automatic equipment and the human problems likely to arise from automation.

What is the Approach of Ergonomics to Practical Problems?

The primary emphasis is upon a scientific approach, *i.e.* upon objective study and the gathering of reliable facts from which deductions and recommendations can be made and proved statistically to have an adequate measure of validity. Opinionative advice and solution are avoided unless specifically requested in preference to no advice at all, and only then with great emphasis upon the unproven and speculative nature of such recommendations.

In tackling specific problems to fulfil the general aim of designing well-integrated man–machine combinations, the ergonomics approach has three definite sections, some or all of which are implemented, according to the type and complexity of task, machine or system being considered.

The first process, more significant with major systems than with individual machines, is to define the system goal and the reasons for having any men in the system, and then to examine and decide which sub-tasks within the whole system should be assigned to human elements and which to machine elements. When considering in turn whether the use of man or machine is more appropriate for a sub-unit, such factors as cost, weight, size, reliability, safety and efficiency, must be assessed and compared for each sub-task separately, and then an optimum balance must be decided for the combination of sub-units into the complete system.

Secondly, for each machine or for each part of a system where the human element is used, the interaction between the man and the equipment must be optimized. To do this, an approach is used which is slightly different from that of the engineer, who rightly must start his thinking from the machine and concentrate upon that. The ergonomics approach at this man–machine level, is to examine the task and the operational sequence that the man will have to do and to consider the man's abilities and limitations and how they will influence the total task performance *(Table 7.1)*. With the man as the centre *(Figure 7.1)* it is possible to work outwards from him, thus firstly examining his interaction with the machine or task *(Figure 7.2)*; this involves studying the operational sequence required of the man in terms of information going into him

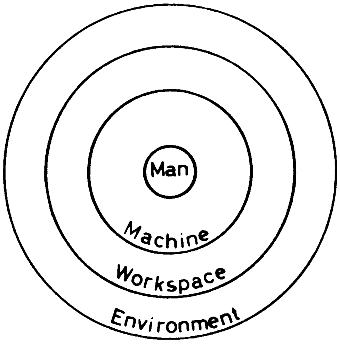

Figure 7.1. The field of study of ergonomics divided into four parts

Table 7.1. The Sector Approach in Ergonomics

I Man

Consideration of:

Sex
Age
Size
Physique
Intelligence
Experience
Training
Motivation

Definition of operational modes required in final situation, e.g.

Searching
Tracking
Monitoring
Decision-making

Thus consideration of abilities and limitations of human operator for all aspects of the task.

II Man—Machine Interaction

Influence on operator and his decisions of:

Displays — sensory input to operator
Controls — motor output from operator
Panel layouts
Display-control compatibility

III Man—Workspace Interaction

Influence on position, posture and reach of:

Machine size
Chairs, desks, etc.
Adjacent machines, structures and material, etc.

IV Man—Environment Interaction

Influence upon behaviour and performance of:

Physical aspects
Chemical aspects
Biological aspects
Psychological aspects

Physical — light and colour, noise, heat, ventilation, gravity, movement, electromagnetic and nuclear radiation.

Chemical — gas or liquid, composition, pressure, smell.

Biological — microbes, insects, animals.

Psychological — workteam, command structure, pay and welfare, shift conditions, discomfort or risk, socio-psychological aspects of the particular factory, neighbourhood, town and type of industry concerned.

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for decision, his actions to signal his decisions, and the compatibility of layouts of panels and equipment with the way he does his work. Next is studied his interaction with the immediate workspace around him *(Figure 7.3)*; the size and position of the chairs, desks, machine console, *etc.*, influence the operator's position, posture and reach, and thus his comfort and efficiency. Finally comes the general environment *(Figure 7.4)* in which he and the machine are at work, including such problems as heating, lighting, ventilation, and the social structure of the group, team or factory of men in which he is; many different fields of science are involved in studying the various aspects of this section.

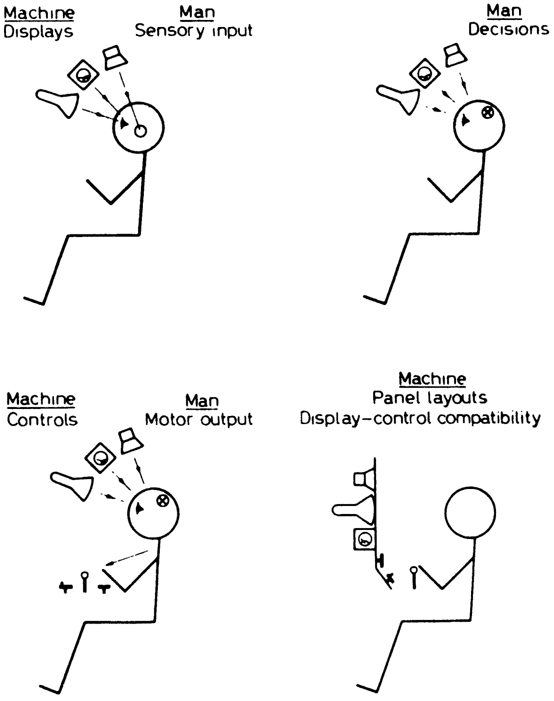


Figure 7.2. Man–machine interaction

To ensure an adequate study and reliable recommendations it is important to consider in turn each one of these three sections of interaction working outwards from the man: *(i)* the machine, *(ii)* the immediate workspace, and *(iii)* the general environment. Only in this way can it be certain that all possible influences upon the man and his work are taken into account.

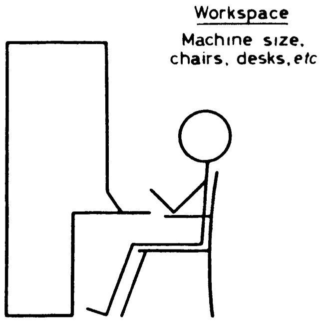


Figure 7.3. Man–workspace interaction

Thirdly, even if redesigning an existing working situation, and especially if involved in the design of a completely new machine system, the proposed and agreed final design should be evaluated by mock-ups and trials to test the validity of decisions on human factor aspects, in exactly the same way that models and trials are used to check important engineering sections of any system. Such evaluation trials should particularly use samples of the expected final operators.

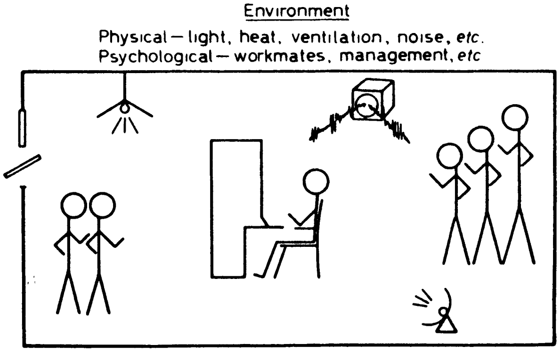


Figure 7.4. Man–environment interaction

The importance of this threefold approach lies in three aspects: *(a)* it emphasizes the importance of defining the purpose of the design process by concentrating first on a consideration of the design problems at a systems analysis level; *(b)* it ensures comprehensive gathering of all relevant data concerning the particular problem situation, and greatly diminishes the risk of wasted time and inadequate solution by premature concentration on the apparent but not real cause of a problem; *(c)* it emphasizes that working situations are dynamic: therefore, to be successful, any attempt to solve the problems of these situations must itself be dynamic, must study the man–machine work as a series of actions and interactions, and must visualize it all as a three-dimensional ciné film rather than as a flat drawing and static blueprint.

Why is Ergonomics Needed?

This question would not be asked if the subject of ergonomics were not mainly human. But because everybody is human, each person tends to think that he automatically knows most of what needs to be known about man when matching up a working situation to him. Whereas in fact the amount of specialist knowledge now available about man is such that there is probably no one man, even a specialist himself, who can learn it and know it all. If a problem arises which is primarily in, say, chemistry or quality control, a person quickly acknowledges if it is outside the limits of his own general knowledge and calls upon the chemist or quality control specialist for assistance. But if he has a problem to deal with involving humans, he still tends to use his own subjective opinion or go to consult the subjective opinions of other men instead of summoning a specialist, perhaps because the existence of specialists is not yet widely known.

Accidents, errors, poor quality and low output are the usual symptoms of a problem which amongst other things, may need ergonomic attention. When a man–machine mismatch in industry today results in such symptoms, the cost of not finding a cure is often considerable but may not be so high as to compel action. But as man in the future is progressively used less for his muscle power and more and more for his ability to process information and make decisions, so he is in control of more assets and more output, and the cost of the mismatch grows in proportion. As with military problems in the past particularly, so now with modern industrial equipment, the demand upon the operator grows as the complexity grows. The more the operator is stressed, the greater is the need to ensure a good match between man and machine to minimize the risk of error and maximize accuracy and output. This is the fundamental reason why the specialist knowledge from ergonomics is needed in modern industry and particularly during the process of design.

Where is Ergonomics Relevant in Modern Industry?

On the shop floor there are many situations where scientifically proven methods of selecting and training operators would yield worthwhile economic improvement. Organizationally, it would seem that these situations can best be dealt with by personnel and work study departments making use of technical data and consultant advice from ergonomics where relevant. In many companies it may not be good economics to employ full-time ergonomics specialist for this work alone.

When new machines and task situations are being designed or considered for installation, ergonomics becomes more particularly relevant, and the cost of obtaining such knowledge, especially if it is sought early enough in the design stage, becomes relatively insignificant in proportion to the typical capital cost involved and the potential savings to be expected.

The same arguments apply with much greater force still as complexity increases and the design of larger production units and systems is considered. A continuous flow production line is a typical example of a modern industrial situation requiring some thorough system design. The bigger such a line is the greater is the importance of adequate feedback and feedforward of information from one stage to another to maintain everything within limits; but very frequently one finds that still only the most primitive means of communication are available between operators, who are now usually at much greater distances from each other. Only thorough and extensive study of what information each operator needs from the machine and each other, and of the way that the system should be designed to present this information most simply and easily, can safeguard against lengthy commissioning time and the risk of costly shut-downs. The emphasis of the ergonomic approach on dynamic rather than static investigation and planning could be very fruitful here.

What Would be Correct Management Policy?

Only broad generalizations are possible, because so much depends upon the nature of a company's product and organization. The manufacturers of complex capital goods are more likely to find ergonomics help of practical and economic value than are manufacturers of simple products. On the other hand, any manufacturer contemplating major capital expenditure on new plant or new production facilities, particularly envisaging a major increase in the complexity of his manufacturing processes, might well save much trouble later by getting ergonomic assistance early enough.

In general, the best criterion is probably the financial size of the company compounded with the amount of man–machine conjoint working time involved, either *(i)* in the consumer's use of the product, or *(ii)* on the production floor, according to which aspect of ergonomics application is being considered. For instance, on the question of ergonomics applied to the design of the company's products, manufacturers of machine-tools, motor cars, furniture and household appliances have much greater need for ergonomics knowledge than manufacturers of electrical generators, tyres, submarine cables and water tanks. Again, on the question of ergonomics applied to production methods, manufacturers with a high ratio of labour to other costs (such as in the boot and shoe industry), with special environmental problems (such as in steel or tyre making), or with important safety considerations (such as passenger transport services), can expect significant improvements in efficiency and safety by applying ergonomics knowledge.

Given a *prima facie* field of application, the scale of ergonomic activity required and the manner of obtaining it will then depend on the size and turnover of the company. In general, it would seem that only large companies, say of more than one or two thousand employees, or those with a large turnover, say of more than one or two million pounds, are likely to feel justified in employing a full-time specialist on their staff. Most managements would be better served by seeking consultant advice when appropriate. This, however, points to the need for one important action. When a decision has been taken to seek ergonomic advice only when required, it is essential to establish, within the normal organization of the company, a clear definition of who is responsible for watching over the general running of the company to detect when and where ergonomic assistance would be economically advisable. Some one or more persons should be given the necessary training and charged with the responsibility of watching for operationally significant ergonomic problems and, when they arise, with the duty of seeking the specialist advice required. In various industries and companies this function is carried out sometimes by the medical officer, sometimes by the work study department, sometimes by the production manager, and sometimes by the chief engineer or his staff.

Therefore, in relation to ergonomics, a management decision is required, in a company of any size, upon the following three points:

(1) What areas of our factory and/or products might benefit from the application of ergonomic knowledge?

(2) Does our requirement justify a full-time specialist or a consultant called in as necessary?

(3) If a consultant is to be used at any time, what department or person shall be charged with the duty of watching for significant ergonomic problems and calling in a consultant in good time?

Conclusion

There are many situations and equipments where ergonomics could greatly improve the operational usage and minimize the waste and 'down-time' which are so often dismissed at present as operator error or ignorance. It is because man is so adaptable that the designer is often able to hide the shortcomings of his machine design behind the skill of the operator, who is rightly proud of that fact. But the more skill required and the less well-trained the operator, the more easily he may break down under stress and make an expensive error. This is not his fault, and the task of ergonomics along with the designer is to simplify the machine design enough and train the operator enough to remove the risk of error but leave the pride of skill.

Acknowledgment

I wish to thank the Directors of EMI Electronics Ltd. for permission to prepare and publish this chapter.

Chapter 8

SOCIOLOGY AND DESIGN

A. M. Penny

Introduction

Sociology *and* design can cover two separate kinds of social situation: the situation of designing and the people concerned with it and planning for it; and the situations for which designs are carried out – what might be called the user requirements area. I shall try to show how different relationships work by referring later to an example of the briefing of an architect of a large teaching hospital, in which I had a hand. This will show some of the kinds of problem which occur, though there will be some, such as the way fashions are initiated and catch on, which I shall not touch on.

Perhaps the basic type of problem of sociology in relationship to design, or rather of sociologists to designers, is the type which would now be called 'two-culture'. This kind of problem applies also to the relationships of designers with their clients and with other people of non-design backgrounds working alongside them in planning teams. This has the rather odd consequence that the relationship of sociologists (and other scientists) to designers does itself present a second level of sociological problems.

There is one further consequence of the form which sociological problems of design take: it is that designers and their non-design colleagues not only relate to an organization in which they work. They also relate to each other and to each other's ideas. The sociologists study the functional situations for which designs are to be prepared. In terms of the way disciplines are usually thought of, these different problem areas would fall within the competency of sociologists proper, social psychologists, anthropologists both cultural and social, and of economists. For this chapter I am taking sociology to include all the fields of these people except the economists.

Since, in addition, designing is an individual business to a large degree in solving problems and in the matter of design judgment, I think that an important group of questions is that of the relationship between social and individual aspects of designing.

The 'Two-culture' Problem

As Sir Charles (now Lord) Snow described this problem, it was the failure of scientists and non-scientists (by which he referred mainly to people concerned with literature) to communicate, and with not wanting to do so.

In the design field also this kind of non-communication is frequent. For example, if the architect of a science laboratory is given briefing instructions to which he works, it may happen that he cannot check that he has understood the needs of the laboratory users as the drawings proceed. If this occurs, as it has been known to do in some university departments, the plans will not meet the requirements. If, on the other hand, there is a regular dialogue between the architect and his client, the final result will be a collaborative effort: the client will work out his needs systematically in a way the architect can use and probably with the advice of the architect. The architect's design proposal can then be checked regularly with the user so that mistakes can be eliminated before too much work has been carried out on mistaken assumptions. In this case there is clear understanding how the client and the designer play their separate roles and how these roles are interdependent.

These two elements, the separation of roles and the way they interact, can be analysed in more detail in terms of their nature and possible solutions to the problems they raise.

I shall discuss first of all the case of architects and scientists working together, partly because I have had experience of this kind of relationship, and partly because it is becoming more and more important.

Many difficulties of the two-culture sort arise just from lack of understanding of their nature. They are called difficulties of communication but the first important distinction is not made as to where the difficulties of communication lie. Are they in the way the communication is made? Or do they arise from what is being communicated? The distinction is between the techniques of signalling (even if it is just putting a message into clear language) and what it is that is in the signal, its content.

It is my contention that the problems are those of content rather than of techniques, though lucidity of communication is essential. It is a further part of my thesis that the kind of understanding which can be reached between people from different backgrounds is of the same kind as one which has been well understood for half a century. I am referring to the kind of understanding which an anthropologist reaches in a society foreign to his own by coming to understand the points of view of the people he is studying. This is an essential part of the fieldwork method which was first developed by MALINOWSKI (1922); the process is the commonsense one (also used by Sherlock Holmes) of the anthropologist putting himself in the position of his respondents, as far as he can. It is called 'observer-participation'.

The Case of Science and Design

To the question: 'Should science and design be mixed?' it is possible to give answers which are for, against, or uncommitted. I am only dealing with the answers for, because the arguments about the other answers do not come into the scope of this chapter. The case in favour of mixing science and design presupposes the possibility of doing so. I think that it is possible but I do not think that the proponents have made explicit how this should be done. For example, LORD LLEWELYN DAVIES, in his 1965 Design Oration to the Society of Industrial Artists and Designers, said:

> 'Today in any field of design the range of technical knowledge which the designer must have at his command is tremendous. Knowledge is also continually expanding and changing, so it is impossible to teach technical know-how effectively in a school of design. Anything that is taught may be out of date by the time the student is in a position to use it. Instead teaching must be directed towards the scientific basis on which technology is founded....'

It would be very unfair to take the statement of the last sentence as it stands, without referring to the teaching methods at the Bartlett School of Architecture which have changed the situation there in so short a time. As I understand it, the students learn about the natural and social sciences because the planning of buildings at the present time has to be based upon reliable information, and the methods of the different sciences provide the best chance of getting this reliability. This approach seems to me to be right to a radical degree. But I do not think the statement 'technology is founded on a scientific basis' either shows how to solve the two-culture problem of science and design, nor does it show the full extent to which results may be carried on solution.

My Argument

I think it is easy to show that science and design (and technology, for the same reasons) are different from each other as activities. Science is concerned with finding out the truth, with discovering regularities in nature and explaining them. Designing (and technology) is to do with making things which will serve a certain purpose for their users.

The question a scientist asks about his discoveries and theories is: 'Is it true or false?' The kind of test he uses is that of falsification. The question a designer asks about his invention is: 'Does it work?' The tests he applies are to confirm that it will work. The problems of the scientist are those of describing, explaining and discovery. Those of the designer are of inventing artefacts which are fit for their purpose, whether this is functional or aesthetic.

These contrasts lead back to the statement: 'Technology is founded on a scientific basis.' Two questions can be asked: 'How can technology be based upon something which is different from it in problems, values, kinds of solution and methods of testing?' and 'In what sense (from at least three) is technology founded upon a scientific basis?' I shall assume a positive answer to the first question to provide the basis for the second. The three possible senses which I can see for the statement are the following:

(1) Technology uses knowledge turned up by scientific methods, and to make reliable planning forecasts gathers information by research methods.

(2) The second meaning includes the first with the addition that technology includes management by scientific business methods.

(3) Open rational criticism which forms the basis of scientific method can also be used on the rational levels of design and technology and has been the reason for modern technology being what it is.

The first two paraphrases are different in kind from the third because of the differences which can occur in the application of rational criticism and scientific criticism. Criticism of a scientific theory includes rational tests to see whether it is internally consistent, whether one part follows validly from another and so on, but also includes empirical testing in an attempt to falsify the theory. Rational criticism can be applied to situations and cases which do not have the characteristics of a scientific theory, for example the truth of a historical statement, or (relevantly to the present discussion) the rationality of a planning or design decision.

Students' training based on the third paraphrase would be far broader than that based on the first two, because rational criticism can be applied to discussion of architectural and design topics which could not in any sense be called scientific. An issue of this kind might be whether a particular theory of design had a rational relevance to a particular design situation, or only an aesthetic one. The conclusions in either case would be quite different. (It is a matter of common experience that some design students argue from an aesthetic statement as though it were rational or factual.)

This argument, I think, shows that design and science *can* be different kinds of activity yet still employ rational criticism. The more local case of the kind of support scientific studies of a sociological nature can give in design is now to be dealt with.

Forecasts

When scientific investigations are carried out to provide 'hard' information in support of policy decisions, such as those taken in planning a building, the people would probably think of the information in terms of research findings or scientific facts, or of recommendations based upon them. I think this is a mistake as I shall try to show by an example. This concerns the amount of storage space needed in a teaching hospital.

I had at one point to find some information about just this problem. I had to provide the planning team of the hospital for which I was working with this information in terms of so many square feet per bed. The simple method I used to start with was to find out the areas scheduled for other comparable hospitals. I found the areas for three others. The figure for each was about fifteen square feet per bed.

It seemed to be reasonable that hospitals were more or less alike in what they stored and in the area this took up in relation to their size. It seemed that this figure of fifteen square feet per bed would be big enough.

It is already clear, I think, that I was not dealing with random facts but with regularities – the more or less constant ratios of areas to numbers of beds. If there had been no regularity the figures would have been useless as such. I was making a forecast based on the assumption that these regularities would apply to another hospital.

I wished to strengthen the basis of my forecast, and I was lucky to find a hospital store which had been purpose-built in the last few years. The ratio of area to number of beds was significantly smaller in this hospital. In this case the kind of deduction I could formulate was this:

Three hospitals have scheduled their storage accommodation as fifteen square feet per bed. One other hospital has a ration less than these. The hospital I was working for was organized on broadly similar lines to the others, so that its needs were likely to be similar. The deduction that I drew was that fifteen square feet per bed was likely to be more than enough for present or foreseeable needs.

The forecast based upon the regularities alone was of a different kind from the second. It was of the kind: 'The sun rises every day, it is likely to do so tomorrow.' The second forecast was of the kind that makes it possible to say that the sun will rise tomorrow at such and such a time precisely, by deduction from Newton's Laws or their successors.

I think it is important that designers, planners, and scientists make use of forecasts or predictions, because it is with the testing of forecasts that scientists can help, thereby validating information on which planning and design decisions are based. I think that it is necessary to point out that some forecasts made by designers are in the nature of untested hunches. A forecast, therefore, may be tested or untested. Forecasting is still a human activity used by designers, planners and scientists, a common highway which can be used for different ends and with different criteria of dependability. It makes a second way in which design and science can share something without any claim being made that they are the same in kind.

The Two-culture Problem as a Sociological Issue

My argument is that there are two stages in this sociological problem, using my broad meaning of the term to include cultural and anthropological problems. Firstly, scientific and designing thinking are cultural in the anthropological sense in that they have a tradition and certain conventions and methods which are handed on from one person to another.

My second point is that the kind of logical criticism I have been using is part of the tradition of science, including sociology. My argument has been about different ways of thinking and the way people who normally do one or the other kind interact. This falls quite clearly into the definition of sociology – the rational study of social relationships.

Example – a Hospital Briefing

When it is decided to put up a new building, such as a hospital, to meet a need which is either not met or not met well enough, the following stages occur, from the realization of the need to the occupation of the new building:

(1) Realization of need and decision to meet it by the responsible organization (committee, board of governors, local council).
(2) Setting up of the executive team to find out the user needs of the building and to deal with the people who will design and put up the building.
(3) Collection of information about user methods.
(4) Formulation of the 'brief' as a whole, probably with the collaboration of the architect.
(5) Various stages of designing to the brief.
(6) Going to tender.
(7) Construction.

In this range of activities and events there is a whole range of social problems. I shall deal with *(1)* to *(3)*, since I know them best.

Realization of Need and Decision to Meet It

With a teaching hospital in present-day conditions the need is usually expressed in the following situational terms:

(1) There is an increase in population, so that the present hospital is overcrowded.
(2) There is need for more space for research and the present facilities do not give any more scope for rebuilding.
(3) Departments have become scattered away from the main hospital.

On this account it is decided to rebuild the hospital already in existence. This simple example shows the following features:

(1) There is an intention to provide treatment and research and evidence of a present shortage of proper facilities.
(2) This intention stems back to more than one set of values. One holds that it is good to treat people who are ill. Another holds that the modern way of treatment based upon research is better than treatment based on superstition.
(3) The intention comes into relationship with the situation stated previously, leading to certain implications if the intention is to be realized.
(4) The decisions are rational to the extent that they have been exposed to rational criticism. If the need for a new hospital could be shown to be non-existent, then pushing ahead with it in spite of this would not be a rational act.
(5) There also appears the important formulation of BARTLEY (1962) that there cannot be any rational justification of a case; a rational argument is one that can be, and has been, exposed to criticism.

Setting-up of the Executive Team

In order that the decision of the initiating body to build can be realized a whole series of decisions have to be taken. Decisions have both a content and a ratification and both of these need people. The ratification can probably be provided by the governing board of the hospital, but it will need a planning team to formulate the content of decisions, to collect information for them and to deal with the different interests involved. The following factors have shown themselves to be important in the appointment of planning teams:

(1) They should be mixed, having medical, nursing, and administrative members, who should be able to understand the points of view of future users of the projected hospital, so that they can offer sensible criticism of the opinions of need.
(2) The architects and engineers should be brought in at an early stage so that they can learn what is going on and help in the formulation of the briefing instructions.
(3) The planning team should have a close internal relationship, involving both seeing each other's point of view and having the chance of discussing and criticizing those of

anyone else. This shows both two-culture situations and the open rational criticism already mentioned.

(4) The planning team has a special formal relationship to its superior body. There is the relationship of a team which finds and formulates the content of the decisions and a superior board which ratifies them.

(5) In the planning team itself there are formal and informal roles so that informal discussions become formalized into minutes and recommendations.

(6) A good planning team can resist pressures from outside and act as a buffer between the potential users and the architect.

(7) Eventually the planning team will produce the instructions from which the architect can work.

Obtaining the Information

This is the stage in which the activities of a hospital are assessed and a projection made for the new one. The obtaining of information means the interviewing of present users who carry on their respective activities in their present departments. The information will be in the form of forecasts as in the case quoted earlier.

The information obtained is used to estimate the terms of future needs and the policies selected to meet them: how many rooms will be needed with their size in each department; what the overall siting relationships should be. Arguments will be given for all the decisions and their rationality will depend upon their standing up to discussion.

The Overall Pattern

I hope that some of the sociological problems inherent in the design of hospitals have shown themselves. These can be listed as:

(1) There is the question of values and intentions in relation to a known situation leading to certain implications. This is a formulation of POPPER, in his *Poverty of Historicism.*

(2) There are problems of formal organizations and their relationships to each other, political, social, and in terms of ideas.

(3) There are problems of the two-culture type caused by people from different backgrounds working together.

(4) There are issues in which forecasts are arrived at on the basis of non-existent information, or information which is scanty or lacking comprehensive test.

(5) Problems become formulated in a multiple way, resulting from the successful solving of communication difficulties between the disciplines of the different members.

(6) There are problems of traditions in medicine and science which lead to the adoption of particular forms of building, or to their rejection in favour of some alternative.

(7) There are questions of interaction between one phase of preparing to build and the next, in terms of how it should be done and managed, who should carry it out, and the passing of clear instructions, all based as far as possible on rational decisions.

(8) There are problems of people from different professions trying not to do each other's jobs but understanding them sufficiently to fulfil a complementary role.

Chapter 9

DESIGN ACCEPTANCE

M. E. Peplow

Introduction

Whereas in the past one has been concerned with whether design effort has been aimed at the most fruitful targets, today there is a public awareness that a valuable national resource is not infrequently directed at wrong targets. This subject is often discussed but one usually lacks a perspective in terms of the frequency of various types of failure and the results of trials of methods of selection of design projects.

The present chapter therefore attempts the limited task of considering the reasons for success or failure of approximately 90 jobs; the jobs being aimed at the design of process equipment and techniques or the solution of allied problems. Using the elements of behavioural psychology as an approach to the customer's system, methods are then suggested for increasing the probability of design acceptance.

Ideas for conducting controlled experiments with such methods are now required and may well follow the pioneering efforts of CHURCHMAN (1961) and HALL (1965). Any results thus obtained might then be co-ordinated by a theory of adoption and diffusion of innovations, such as that recently propounded by ROGERS (1962).

Outcome of Completed Equipment and Process Design Jobs

A survey was recently made of the work of a research, design and development (R & D) department that was formed six years ago with five professionals and now has 45 professionals and the same number of support staff. The department serves, in a particular region, a large number of dispersed specialized production units and aims to: *(a)* examine plant processes, for the purpose of providing new knowledge upon which to base new or improved designs; *(b)* design and develop process equipment and techniques; *(c)* solve certain operating problems; *(d)* provide a specialized test service.

Approximately 90 jobs have been completed in the creative categories *(a)* to *(c)* and a similar number in the test category. There are also 90 current jobs, over half of which have been actively pursued for more than a year. The jobs were started by 'customer' request; by R & D department initiative; or by suggestions from various HQ officers. The outcome of the 94 creative jobs, in terms of implementation, is as follows:

48 successful – accepted by customers.
8 successful – equipment for R & D department's own use.
8 negative – *i.e.* a current theory or design concept disproved.
12 partly successful – *i.e.* partly failed or a slow adoption.
18 failed.

This failure rate lines up with that reported by the 1960 Federation of British Industries Survey but is much less than private report gives for consumer goods in the USA (BOOZ, ALLEN and HAMILTON). It was found that a failure rate, for process development and new products, of one-sixth was 'remarkably constant throughout the whole of industry'.

The present failures lie more with the basic jobs started by R & D initiative. Advice was of course sought from senior people whose judgment was based on observation and past experience of customer operations. However, not only do judged needs sometimes differ from actual needs, but the latter can change with time. On the positive side, it has been found that 10 per cent of all the jobs have given useful by-products. Thirty of the successfully implemented jobs were customer's direct requests. The remaining 18 were characterized by:

5 solved a customer's recognized problem.

1 helped a customer's own development project.

3 gave a good cost or time saving (but not all such jobs were implemented).

6 were implemented at a future date, when a severe operational problem occurred.

3 were the subject of continuous sales pressure.

A similar analysis of the 30 part or complete failures with respect to implementation gives:

7 were technical failures.

8 were economic failures.

15 failed due to personality factors.

Design Failures on Technical Grounds

The technical reasons for the seven failures were:

Inadequate initial specification.

Inadequate design.

Unscientific approach.

Insufficient study of existing designs.

Problem unsolved within set man-time resources.

The consequences of an inadequate specification, or one not agreed with representative customers, were:

Inflexible (or even unsuitable) design.

Overcomplicated design.

Design failed to cope with a critical factor.

In respect of the latter, some failures could have been avoided if other engineers and scientists had been consulted on the possible boundaries to the problem or used to ensure that a traditional approach was not used inappropriately for a new type of problem.

Designs were mainly inadequate because they provided insufficient improvement on existing designs and inexperience contributed to this. Occasionally inefficiency, unreliability, complexity or oversize were factors. The unscientific approach entailed:

Lack of initial applied research (unverified or unanalysed ideas and underestimate or disregard of basic parameters).

Lack of accelerated life tests.

Basic knowledge lagging too far behind the technology.

Lack of perseverance with a particular concept.

Although many design problems will appear to be solvable by means of an existing approach and no-one wishes to spend time on unnecessary research, it is suggested that the decision to follow the trial and error trail should only be made after unhurried deliberation.

Discussions with other engineers and scientists have indicated other causes of technical failures. A list is given in Appendix A at the end of this chapter.

Design Failures on Economic Grounds

The main cause of failure here was a change in the commercial environment during the period of research, design and development; particularly if the job had been a prolonged one. Changes in the customer's operations, maintenance or material supplies and the advent of competitive designs are also involved. Forward looking economic feasibility studies and continuous contact with customers might keep the amount of abortive work to a minimum. It is particularly important to give the customer an idea of the cost of the intended equipment at the earliest date.

Sometimes a competitor's design was found to be better or cheaper, particularly if a development had been started without a 'brainstorming' or other search for a variety of initial design concepts. Even in the absence of a competitor, the development or subsequent production cost of a device could be out of balance with the value of it to customers. Improvements in estimating, based on planned development, therefore seem necessary.

Where a design is to be put into production by the customer, it may be essential to study the latter's internal organization before deciding which of the possible designs can be economically handled. The alternative can be a considerable waste of effort on a specific design.

Some other causes of economic failure are given in Appendix A.

Design Failures due to Personality Problems

Half of the failures lay in this area. The main cause of failure was apparently due to the customer being too busy to implement a plant or other improvement, even though he accepted its value. Recognizing that everyone has his priorities, consultations are needed before embarking on proposed research or design work. However, it may sometimes be possible that the priorities of those responsible for design implementation are out of step with higher management policy, due to misinterpretation or the fact that a rewards system cannot line up perfectly with a policy system. For example, there may be a policy of keeping production going *and* improving the process or product; whereas career rewards may appear less linked to improvements, even when these can be detected in trends or framed by targets or competition. There may even be a misconceived fear that an improvement venture which fails will interfere with career progression. Other personality difficulties found in the way of design acceptance were:

Customer's interests change during the design period.

Customer prefers to await a universal solution to his problems.

Reversal of a particular policy with a change of management.

Suspicion of a process only verified on model scale.

Organizational structure incompatible with innovation (CARTER and WILLIAMS, 1959; BURNS and STALKER, 1961).

Duplication arising from personal competition within an organization.

Design limited by customer's attempts to reduce the cost.

Designer fails to obtain or keep the customer's support for his ideas.

Designer fails to persuade the customer that risk involved in design acceptance is justified by the potential benefits.

Customer unwilling to change his procedures or retrain his operators.

Prestige of people who must advise or agree to a design is involved. (Sometimes the 'not invented here' attitude.)

The Designer–Customer Relationship

The last four items of the above list are examples of a failure in the designer–customer relationship or failure to keep in mind that, for design as for beauty, 'the value lies in the eye of the beholder'. To probe this, one can consider the psychologists' concept of basic needs which humans strive to satisfy, directly or indirectly (MASLOW, 1962). The basic needs are usually listed as:

Physiological – air, food, *etc.*
Security – orderly, predictable world; freedom from worry.
Emotional security – belongingness.
Self respect.
Others' respect – status.
Self expression – self actualization.

The last two needs are difficult to satisfy fully and so are the ones to which a new design can be addressed. It should be noted that self expression includes gaining a personal understanding of the mental, emotional and concrete constructs of others as well as personal creation of these. Financial rewards can, of course, lead to the purchase of goods and services which help to satisfy some of the basic human needs. And job easement can provide the time for obtaining the satisfaction of needs.

Analysing further, one notices that an individual may seek self expression, *etc.* in one or more of about eight main fields of interest (ALLPORT, VERNON and LINDZEY, 1931). Relevant to design acceptance are the following:

Economics – production of goods and services.
Political – power, responsibility.
Social – helping others.
Theoretical – rational understanding.
Concrete construction.
Aesthetic.

The individual personality may of course see the field in a conservative or a radical light.

The Customer

In the customer's eyes, a new design is acceptable if, in relation to the effort required of him, it fills one of his needs previously unfilled or incompletely satisfied. However, he may not realize that there is an aspect of the design which could meet such a need. The designer or his agent must therefore get to know the customer's needs so that, through a detailed knowledge of the design, the most relevant aspect can be identified and drawn to the customer's notice. The questions then become:

(1) Does he seek one or more of status, self expression, job-easement, financial reward?

(2) Has he a strong interest in the economics, politics, social, constructional, theoretical or aesthetic field?

(3) Is he conservative or radical?

(4) Does he fear failure to cope with change?

This method of tracking down customer's needs is probably unnecessary to those with 'social intelligence' or an intuitive knowledge of the likely behaviour of others. On the other hand, some of us need, in addition, to know from the psychologist the type of indirect question which will yield the clues to a man's basic needs and interests. An alternative approach is to show, in a conspicuous manner, that a new design can contribute, significantly and in a reasonable time, not only to financial success and job-easement but also to status and self expression in the fields of practicality, social usefulness, ingenuity and harmony: at the same time too conservative or radical a tone should be avoided. The lower the level of a customer, the shorter is the time he is likely to accept as reasonable and the more predictable must be the consequences of any change. Thus slowly maturing investments should only be recommended to a high level. Although the need for belongingness may encourage lay customers to follow a fashion, in respect of technical people it usually arises as a need for maintaining a particular group culture; leading to the granting of mutual favours as well as an attitude to innovation in line with group norms.

The 'not invented here' attitude, which often takes the form of finding a possible snag in an offered design, can be understood in the above terms. Acceptance of a design may be perceived as a deterioration in relative status, outbalancing the gains which acceptance could bring. It may also interfere with doing a job 'in one's own way'. Equally understandable is the difficulty of gaining an acceptance of a rational proof that the customer's contrary proposition not only has snags but is bound to fail.

A brief indication of the relation of customer to new design adoption, in terms of Rogers' ideas, is given in Appendix B.

The Customer Without Needs – Whereas a man dissatisfied with his plant is likely to welcome help in his creative endeavours to improve it, the satisfied man is usually a poor customer. As one of the greatest men of our profession, Edison, wrote: 'show me a thoroughly satisfied man and I will show you a failure'. Since progress entails risk-taking, one might also say: 'show me an unventuresome man and I will show you a failure'.

Customer Survey

Where reports of new process equipment, techniques and principles are circulated to potential users, it is possible to invite comments and ask questions such as:

(1) Is the subject of the report relevant to your problems?

(2) Is the presentation suitable?

(3) Has sufficient work been done?

(4) Are the results of use now or possibly in the future?

Even though it was realized that some of the answers received would be guarded opinions, each of 45 potential customers were sent a questionnaire in respect of one of several recent reports. The simplified chart in *Figure 9.1* shows the numerical distribution of questionnaires (fraction denominator) and replies (fraction numerator). The figures in parentheses give approximate distances from R & D, in miles.

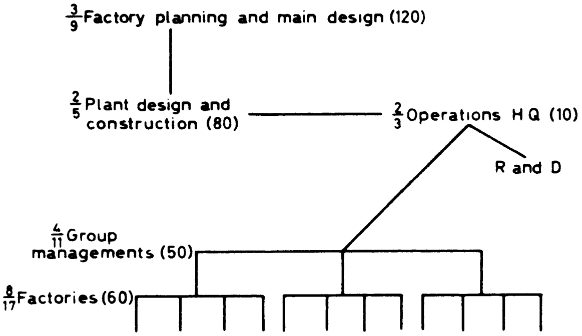


Figure 9.1. Numerical distribution of questionnaires and replies

Although the R & D personnel perceive their role as equal service to all the other branches, the two branches making by far the most demands on R & D are the two that returned the biggest proportion of their questionnaires. Particular features of communications with these two branches are: *(a)* one branch is geographically much nearer than all the others; *(b)* R & D people are frequently at the factories (the other 'branch') since the latter provide facilities for R & D fieldwork on local and general problems.

The reactions to the reports were:

(1) Reports from R & D encouraged.

(2) A few felt that presentation could be improved by emphasis on illustrations, summary data sheets and examples of practical applications.

(3) Other than where the report met a specific request, the belief was expressed that it was helpful in small ways and could be of benefit to others, rather than a stated intention to act.

These comments show a sympathy to R & D but underline the need for adequate customer consultation before investing much effort, and the need to present results in terms that are both easily understandable by customers and couched in terms of their interests.

The poor response to the questionnaire was associated, in the case of one branch, with the difficulty of dealing with an over-abundant supply of information. Conversely, a special effort to disseminate leaflets on new equipment to the user level was frustrated by filtration, at a higher level, that was no doubt intended for saving the reading time of others. The exercise of local imagination in the light of detailed local knowledge was thus made impossible. Although one is drawn to personal communication, which is more effective since it is difficult to ignore as well as allowing illustration and questions of elucidation, the time involved for both parties can be very great.

The Designer

One can appreciate the designer's need to wrap himself around his design problems and his possible annoyance if requested to distract himself and talk to production people and potential customers. For some designers, there is also a need to avoid the risk of a 'loss of face', occasioned when an idea eventually proves to be misconceived. There is sometimes the fear that the proprietorship of the scheme may become doubtful, after early disclosure.

Against this is the need to establish, under changing circumstances, the production, economic or time feasibility, and to build up an understanding of the customer's personal and technical needs. R & D management are thus placed in the position of establishing a system which measures success in terms of design acceptance and rewards on this basis. General management may find it necessary to ensure that co-ordination, between the various functions of research, design, construction and user, occurs at the problem-solving rather than solution-accepting level and starts at the first inception of any new scheme.

Multi-department project teams with a responsibility for particular types of development or improvement work is one method of organizing this type of co-ordination, so long as executive authority is given to implement or demonstrate schemes. Experience has shown that members of a project team that produces data for one of its member departments can feel that they are only presented with parts of the problem and that decisions are biased. Under this arrangement, it is difficult to sustain everyone's best endeavours.

Design Planning

Design acceptance can be jeopardized by skimping in the final stages. This is sometimes traceable to a designer becoming concerned that if he requests much further time, to meet a late difficulty, then this may be judged as a sign of his incompetence. Perhaps one answer here is to insist on man-day estimates against each item on a list of the various sequential activities in design work. Delays in the early stages will then not be able to eat into time properly required for the later stages.

Another cause of weak final stages, or the lack of an adequate 'hand-over' of data and background, is due to the pressure of new, urgent jobs. Department planning should therefore try to keep a uniform rate of job closures and balance this against a rate of job starts that more than covers urgent work. There must obviously be a sufficient number of people in each of the necessary professions to allow this rate of job closures.

Conditions Favourable for New Designs

Although growth and keenly competitive industries are more likely to encourage or accept the trial of new equipment, much can be done to favour new methods in all firms. The author is associated with an industry where the number of links between functions within a firm and between supplying and purchasing firms is continually increasing, with the aim of encouraging improvements and new developments. Within the firm, for example, standing working parties comprised of operations, design and development engineers examine plant design defects and operating difficulties. This activity can lead to a team spirit and a common language which assists in the acceptance of innovation outside the working party remit.

Collaboration between a customer and his suppliers may appear difficult, when the latter are in competition, but areas can be found where the cost of potentially useful research is too great for an individual firm or where the creation of new data will not inhibit a variety of competitive designs.

A technique for forcing new designs is reported in the 1961 ZUCKERMAN report to the Minister of Science. This is exemplified by the Development Group of the Department of Education's Architects and Building Branch, which is designed to bring scientific and technical knowledge to bear directly on the formation and efficient execution of building policy and is an integral part of the Branch responsible for approving building projects. The Group, for example, is given the responsibility of building a required school, whilst at the same time attempting an improvement in building design, components and methods by exploiting applied research results that have become available and by scientifically analysing all the normally accepted assumptions. Since financial discipline is imposed, a system of cost planning is necessary and this provides a common language for the collaborating professional and lay parties. These comprise people representing the policy-makers, teachers (users), development architects, surveyors and engineers as well as co-opted designers, suppliers and builders.

Attempts to Improve Design Acceptance

The work that was started by the new R & D department in 1959 began to mature in 1961. During the next year, some failure of design acceptance was noted, particularly in respect of jobs started by R & D initiative. Approaches to improve the situation for these jobs took the form of: *(a)* obtaining, where possible, a sponsor; *(b)* in the absence of a sponsor, conducting the fieldwork at factories where the management was keen on innovation.

Table 9.1. Implementation Results

Period	Successes* (%)	Part Successes† (%)	Failures (%)
Up to April 1964	55	27	18
May 1964 to April 1965	71	8	21

* Includes equipment or technique for R & D department's own use.
† Includes work to disprove a current theory or design concept.

The effect of such approaches should have begun to appear during 1964 and a comparison was therefore made of the 28 jobs completed between May 1964 to April 1965, against the 66 jobs completed in the period up to April 1964. The implementation results are shown in *Table 9.1.*

It will be seen that although the failure rate remains unchanged, there is an apparent swing from partial to full implementation.

Conclusions: Proposed Methods for Improving Design Acceptance

Based on the facts presented and the attempted interpretations, it is suggested that experiments could be conducted to prove whether the adoption of any of the following methods, at particular stages of the design process, can significantly increase the acceptance of new designs of equipment and techniques.

Before Design Work Commences

(1) To identify a customer's needs:

(i) Obtain an adequate knowledge of his outlook, his perceived functions, and the work problems upon which innovation may be perceived as intruding.

(ii) Test out his need for self expression by relating the proposed development to his own, possibly latent, schemes or by attempting to share the creative work with him.

(iii) Consider the nature and relative priorities of the demands on his time, other than for innovation.

(iv) Set up, where appropriate, a Multi-Party Development Project Team or otherwise prevent the conflict which can arise between departmental aims (*e.g.* bring the rewards system fully into line with company policy).

(v) Agree an adequate initial specification of the problem or requirements.

(2) To assess feasibility:

(i) Carry out a thorough analysis of the technical needs.

(ii) Estimate development and likely implementation costs by constructing a detailed plan of the work.

(iii) Test out the likely costs on potential customers.

During Design Work

To increase quality and relevance:

(i) Avoid, wherever possible, the trial and error approach.

(ii) Generate a sufficient number of initial design concepts before a final choice is made.

(iii) Consult other professionals, to ensure possible critical factors are recognized and fully assessed.

(iv) Check back frequently to representative customers, to ensure that the design work keeps in phase with changes in their understanding and in the commercial situation.

After Design Completion

To present the design to a customer:

(i) Ensure his interest is caught. (This may involve the cost of a personal approach.)

(ii) Use his language.

(iii) Relate the design to his personal needs.

(iv) Prove that the design meets one of his needs (*e.g.* successful adoption by one of his colleagues).

(v) Show that the steps he will have to take are convenient and practical.

Acknowledgment

My thanks are due to Mr. R.H. Coates, South Western Regional Director, Central Electricity Generating Board, for permission to use the various facts collected in the course of my official work. The opinions expressed are, however, personal.

APPENDIX A: Equipment and Process Design Failures

Technical Causes

Inadequate initial specification.

Inadequate design.

Unscientific approach.

Insufficient study of existing designs.

Problem unsolved within set man-time resources.

Incompatibility with existing plant system.

Sub-designers not consulted when scheme later modified.

Design beyond average craftsman's skill.

Insufficient manufacturing control.

Equipment beyond average operator's or maintenance man's skill.

Customer lacks background for dealing with application problems.

Economic Causes

Change in the commercial environment.

Competitor's design best.

Development or subsequent production cost too great.

Incompatibility with customer's internal organization.

Market too small.

Each customer required special modifications.

High installation or maintenance costs.

Customer paid for a design which he might have needed quickly at a future date.

Personality Causes

See p. 67

APPENDIX B: The Design and The Customer

Rogers, in his valuable source book on innovation research, shows that a number of concepts are relevant to the adoption of new equipments and techniques. It appears worthwhile to attempt a validation of such statements regarding maximum adoption as:

The *Design* must have

Simplicity,
Ease of demonstration,
Sample trialability.

Ability to give customer satisfaction, within his social group's norms.

High relative economic or social advantage to the social group.

Compatibility with the social group's past experience.

The *Customer* must have

Youth,
Outward-lookingness,
Relevant specialization,
Opinion leadership,
Dissatisfactions.

The *Social Group* must have

Modern values (rather than traditional ones).

PART III

THE ELEMENTS OF DESIGN

Chapter 10

A MORE DETAILED VIEW OF DESIGN

S. A. Gregory

Introduction

This section of the book provides an analysis of the activity of the designer in his response to the environment and his own inner drives. He is the link between opportunity and realization, between the situation and the product, and by his action may contribute to them and change them. He is bound by the logic of his own mode of working and by the constraints of the design task.

In Chapter 11 Watts sets out to provide a model of the designer at work. This model, which he terms an iconic model, is abstract and does not attempt to reproduce the features of a designer and his environment except in so far as they represent the key logical relationships which the dynamic activity of design requires.

Watts uses a model which appears at first sight to be somewhat abstruse and couples it with the language of set theory and of general systems theory. His reasons for doing this are compelling. He uses set theory in order to provide general rules and the subsidiary rules which are enclosed within them: necessary relations or consequences thereby become exposed and obvious. This development based on logic is later supported by the practical evidence of the various methodical procedures in design, particularly those of ARCHER (1965) and of LATHAM, TAYLOR and TERRY (1965), the latter being better known as PABLA (problem analysis by logical approach). The implications of set theory hold not only for determinate situations but for situations in design in which the outcome is uncertain or unpredictable in practice. For such situations strategies have to be developed: GREGORY (1966) has discussed the relationship between such strategies and the total design situation in dealing with the problems of new process design.

In the model which Watts proposes he stresses the autonomic aspect of the designer. This means that the designer or the design team has to be responsible for the decisions made. Watts makes the point that at some stage it may be necessary to refer decisions to higher authority. This may be because of the constraints of the situation, or because of lack of potentially ascertainable information, or because uncertainty has to be absorbed. For his paradigm or model of autonomic activity he turns to general systems theory, which, as a theory of general models, includes within its scope the theories of different aspects of systems behaviour such as communication, control, learning, adaption, *etc*.

It is within this area of autonomic activity, which includes the possibility of the exploration of the environment for alternatives, that the methodical procedures for design which owe some of their inspiration to work-study should be placed.

WADE (1960), formerly at Gosta Green, but now with the Engineering Employers' West of England Association, seems to have pioneered the application of the work-study approach. This has been followed by the well-known development of design teaching at Bristol which is dealt with by Matchett and Briggs in

Chapter 21. The technique, in a form known as Critical Examination, has been developed inside Imperial Chemical Industries Ltd., particularly in the Dyestuffs and Mond Divisions. Aspects of this have been provided by BIRCHALL (1960), BINSTED (1960) and BAXTER (1961). From the United Kingdom Atomic Energy Authority, WOLSTENHOLME (1962) has made a general appraisal of work-study in design.

Watts turns to the work of MESAROVIĆ (1964) within general systems theory and his development of the foundation, largely in terms of set theory. This work of Mesarović has been conveniently summarized in a piece of doggerel by BOULDING (1964):

'According to Mesarović
A set of proper statements which
Has mastered, in well-ordered schools,
A set of transformation rules
Which rules in turn have rules to twist 'em
Deserves the name of general system.

All systems, it is now proposed
Are either open, or are closed.
The closed have one-to-one relations
But don't result in innovations.
The open are disturbed, adaptive
Or Heisenberg-observer-captive.'

The model designer is depicted as moving spirally upwards on the surface of a vertical cylinder, rising from the abstract to the more concrete, and cycling successively through zones of analysis, synthesis, evaluation and decision. Watts emphasizes the fact that these changes of activity cannot be separated completely and that much of the work involved is preconscious.

In his view the designer is submerged in information of the kind which McCrory discusses in Chapter 2. Not all designers undergo the same sort of experience, many suffering a shortage of information. This, in turn, leads to a search. For this reason it is sometimes thought better to observe this zone of activity as one of search and analysis.

Watts indicates the importance of some device for sorting relevant information from 'noise' and this holds true whether the designer is submerged in information or has to search for it. This item in the perception machinery tends to sort or organize information into sets of some apparent relevancy, usually, for practical purposes, sets with as little interaction as possible. He makes clear the fact that some attention has to be accorded to the treatment of 'isolates', in the terminology of LEVY (1938). Components need to be regarded in terms of their interactions in order to obtain a satisfactory summation.

The model of the activity of the designer put on the external surface of the vertical cylinder is topologically the same as the activity recorded by ASIMOW (1962), provided that the cylinder trace is unrolled. SCHER (1965) has discussed a version of this process. Watts himself sees Archer's latest network scheme as the best available paradigm, including, as it does, working rules in considerable detail. How far this may be maintained will probably depend upon the type of work involved, upon whether the design is design of a system, or whether it is radical or novel design.

Watts considers the case of system design as such, *i.e.* the design of an artefact having interrelated components and a pattern of input–output behaviour involving motion, energy, material, or information. Concepts for design may be generated by varying the component characteristics whilst maintaining the interconnection or morphology. This gives rise to a sequence of steps termed the morphological approach. This interpretation of the morphological approach to design is rather more in line with the viewpoint of NORRIS (1963) than might be gathered from the frequent references to ZWICKY (1948) who coined the term. Even here, as a possible technique in the design of systems, the morphological approach, as seen by Watts, represents a member of the set of approaches in system design. The scope of the set of approaches is probably best given by GOSLING (1962).

The work of Zwicky may be viewed in a number of different ways. It may be seen as related to methodical exploration techniques, such as the tree method discussed by Eder in Chapter 3, or the matrix method. The original morphological method, without any system attachments, provides also a foundation for certain creativity techniques, as mentioned by Broadbent in Chapter 14.

The chapter by Watts represents the most substantial attempt to date to provide a plausible model of designer behaviour in formal terms. Its power may be gauged by the way in which it is able to bring together the principal recognized methodical procedures for design which have been listed in this chapter. The reader is encouraged, therefore, to make the attempt to familiarize himself with the argument which is put in terms of currently available theory. For man–computer design, as discussed by COONS (1963) some such formalization is useful.

For an introduction to the way in which models may be used for specific design problems the reader is directed to Chapter 17. But before trying these it is recommended that reasonable efforts should be made to draw such useful consequences as there may be from the general approaches. System design is particularly susceptible to treatment in this way.

The Handling of Information

In Chapter 12, Farradane deals with the topic of information for design. Design may be seen as essentially an information processing system. Indeed, activity studies and analysis of designer behaviour (*e.g.* the study of design office behaviour by TURNER, 1964), stress the large amount of time needed for the collection, reading, discussion and testing of information. Farradane is primarily concerned with the way in which concepts are handled by the human brain in order that mechanical assistance may be correctly developed. For Farradane the important tasks of information processing are those of collection, storage and retrieval. In these cases the information is external to the designer and has to be handled externally.

This information consists of concepts of what may appear to be in the external world. Although designers must themselves pursue the information that they need, it is possible for them to be helped by the specialists who process information and who study the nature of information.

Storage and retrieval depend upon some kind of structure in the information. Already reference has been made to the need to deal with an excess of information by some filtering device, or, if search is needed when information is scarce, to have some guide for selection.

Farradane sees the method of developing possible relationships between concepts in terms of practice which has been identified in problem-solving. This is justified, in particular, by the researches of PIAGET (1953) and GUILFORD (1959). The latter, in his work on creativity, has stressed the nature of operations, products, and contents. The operations are those involved in problem-solving: perception, memory, convergent thinking, divergent thinking, and judgment. These concern products which are essentially arrangements of concepts. It is upon this kind of basis that Farradane has developed a system which classifies in terms of nine categories of relations. This classification has been checked against 10,000 items.

In its present state Farradane's system in concerned with semantic information, *i.e.* written material, and does not deal with visual material. It presents the normal range of static relationships between such concepts. Although this provides a substantial coverage there is still the problem of preparing for the future, for repeatedly different aspects of information. There appears to be little immediate prospect of having initial analysis done by computer. In spite of the difficulty of analysis it should be possible to transfer the logic of the present system to the computer.

It is hoped that some development of the present logic may be discovered which will permit the mechanization of creative thought processes. ENGELBART (1962) and ROSS and RODRIGUEZ (1963) suggest some lines of work in connection with computers.

A Speculative Model of Pattern Production

If methods by which design thinking might be transferred to the computer are to be developed, possible ways in which a computer might carry through such operations must be considered. At the same time light might be thrown on the way in which the brain works by starting from consideration of possible modes of computer operation.

In Chapter 13 Newman puts forward some speculations which go along the road to fulfilling part of these ambitions. In his thought about how a brain might work the central feature is the pattern. The pattern contains a hierarchy of bits and shapes. This may be well represented by a network of lines. The properties of such a network of lines may be discussed in terms of graph theory.

Such a network may also be seen as a definition of procedure. In passing through such a network the action at any junction or node may be influenced by what happened at the previous junction. A characteristic of nodes is their 'connectivity'. A network may be seen as a pattern of connectivity. In a pattern there may be many isolated procedures; there may also be dense regions interconnected by tenuous links. With simple networks it is possible to follow through the alternative kinds of behaviour which develop according to the value of the initial impulse fed into the network. With a complicated network or anastomosis, however, it is difficult to predict what is likely to happen.

Newman points out that a network of the type that he describes may be taken as a computer programme. But his programme has more 'degrees of freedom' than a normal programme. It is possible to develop a set of nodes to deal with any logical situation. It is also possible to set up models which will provide 'language-type' patterns along the lines indicated by Noam Chomsky. (An introduction to this topic might be gathered from PUTNAM, 1964.) Chomsky sees the need for a complex transformation system to make sense of a stimulus–response model as far as linguistic behaviour is concerned. Newman gives as example the phrase 'old cow'. The response to this stimulus will depend upon the immediate environment and previous experience of the listener, and possibly other things.

'Meaning' according to Newman suggests a special structure in each cortex. This might be isolated, as a programme, by 'killing' all the nodes around it thereby rendering it precise. But in any living situation it is attached to the whole of the cortex and the whole of the cortex may be in action during the operation of the programme concerned. Given such a model of meaning it is possible to understand better the way in which humans recognize words or visual patterns.

The identification of patterns and the generation of patterns are implicit in design. Information has to be accepted by the restricted input system of the human being (45 bits per minute?) according to some pattern. The pieces of information have to be arranged to provide some hierarchical pattern. It might even be that the autonomic model experiences relief, even an aesthetic reaction, on achieving the required pattern following the practical activity of design.

On Practical Techniques of Stimulating Creativity

From the model of the autonomic brain, which in turn can be seen as a possible explanation of the specific design behaviour of the iconic model of the designer, it is no long step to the consideration of practical techniques of creativity. Here arises concern with finding the kind of stimulus which will produce, or assist in producing, a creative response. This may be anything from a simple word to a challenge at the TOYNBEE (1960) level of history.

Each individual has his own mental equipment and his own experience. Is it possible to provide a stimulus which will directly produce a creative result? Is it possible to restructure experience or mode of thinking to yield a valuable result? Can the individual be put into some fresh relationship with other individuals and/or machines to facilitate the necessary transformations?

In practical situations creative work is likely to involve something much more complex than simple logical transformations. The evidence suggests a considerable depth of personal involvement. This goes beyond the intellectual information processing model largely suggested by Watts, although he recognized the considerable extent of preconscious work. In some way yet undefined in any model, the interaction of the life process of a specific designer with his task must be accounted for.

Broadbent, in Chapter 14, proposes a simple model of creative behaviour, which has relationships to other models developed in the book. He thinks in terms of a stimulus–response situation in which the incoming stimulus is compared with constantly changing basic patterns. He believes that the imaginative designer has either intrinsic flexibility in his patterns or the ability to restructure them readily. He emphasizes the fact that this ability may lie in dealing with a specific kind of material, such as words or visual patterns. It should be noted that conferences tend to attract verbalizers whereas many designers are visualizers. SMITH (1964) has recently come to the defence of the visualizers.

The techniques which he proposes to assist in the drawing out of existing creative ability include check-lists, interaction techniques, and free association methods. These tend to be verbal in character and some effort might be devoted to extending visual methods: already the designer is aware of the stimulating effect of freehand sketching.

Discussion of creativity inevitably raises the question of its adequate definition in such terms that it can be measured. This problem has been treated in some detail in the book edited by TAYLOR (1964), particularly by BROGDEN and SPRECHER (1964). Creativity is bound up with value, and value changes with the circumstances. Creativity, just like design, is involved in the product, in the process, and in the situation. An attempt is made to link them in the GREGORY–BURDIS model (1965). This should be seen against the Watts model of design.

Value and Design

The practice of design turns upon some system of values, whether intuitive or conscious. A product is designed because it is held to be of potential value to a consumer. The consumer may find one manufacturer's product more valuable to him than that of another manufacturer. The product itself will have a different value to the designer.

The consumer, particularly if he is a government department, may make some choice which appears to be nothing but arbitrary, but henceforth the designer may have to take this arbitrary choice and use it as the standard against which to evaluate the major and minor factors in his design. The choice provides a pattern in relation to which alternative possibilities (information, shapes, components) are selected or ranked.

Does the autonomic designer operate in a universe of absolute values, or does he have built-in values special to himself; are the values imposed for the occasion; does he develop them for himself, or are they random? How far, indeed, is he autonomic?

Pleydell-Pearce, in Chapter 15, tackles the discussion of value from the standpoint of the philosopher. He puts the arguments in a very general way, hoping thereby that people will not become emotionally involved.

He finds that values may be instrumental, arbitrary, or through exemplification. An object may have instrumental value through its ability to help some further aim. An arbitrary value may arise from some preconscious choice; but, in rational situations, arbitrary values must also occur since there is a practical limit to search for rational explanation.

Such a discussion of values is of particular significance to those designers who have to deal with intangible and non-quantifiable values. Architects and planners find such problems and the predicament of the planner has been discussed by LICHFIELD (1964). But it should be noted that in potentially quantifiable systems the concept of optimum may be meaningless.

Decisions

The philosophy of ethics is largely devoted to exposing the arbitrary nature of theories of value. This is not to suggest, however, that theories of value should be thrown away, but that they should be treated with the relevant amount of respect. Rational decisions are not possible without value systems, whatever the values may be, instrumental or otherwise.

A decision, particularly a design decision when taken in modem society may affect many people, and may involve the expenditure of substantial resources. Decision implies responsibility for action and outcome. It is preferable that the decision should be made on bases which are communicable and acceptable. This implies some kind of rationale and rationality.

Decision theories have been developed with the hope that they might provide such a basis of conviction. There are serious difficulties involved in practical use of either games theory or statistical decision theory. This is discussed at length by FISHBURN (1964). The essential difficulty lies in the treatment of probability for a single occasion. Furthermore, at the outermost boundary of the decision, the value is unlikely to be simply determined. Methods of handling non-linear value expressions and subjective probabilities may be combined to give expected utilities or expected relative values. Mathematical expressions of this kind, although intuitively acceptable, require quantitative values for practical applications. Such quantitative values are most unlikely to be obtained in a decision-bounding situation.

In industrial design organizations the criterion of decision operated by the board of directors is not readily discernible. It is usually stated in oversimplified terms and the finer details people are expected somehow to assimilate by absorption from the atmosphere. WILLIAMS and SCOTT (1965) have studied the background to decision on investment in the case of fourteen firms. They find that the goodness or otherwise of a decision cannot be judged by any of the simple criteria proposed for investment analysis and that there must be some study of the context of the decision. The decision, so to speak, only has meaning in a particular background. This agrees with the heuristic appraisal method of GARGIULO and colleagues (1961). The problem is analysed by SHUBIK (1964).

It is possible to visualize the investment criteria of a company as the outer boundary within which subsidiary decisions have to be carried through. The directors' criteria should comprise the set of all decision criteria likely to be operated in the company. Actually the company is an open system and opportunities for change may exhibit themselves to different levels in the company. Technical opportunities are likely to present themselves without entering the practical range of the directors' decision criteria. In the last analysis the individual designer has to make his own decisions, even decisions whether to refer to higher level. Concern is, therefore, with the designer's own motivation and his structure of expected relative value.

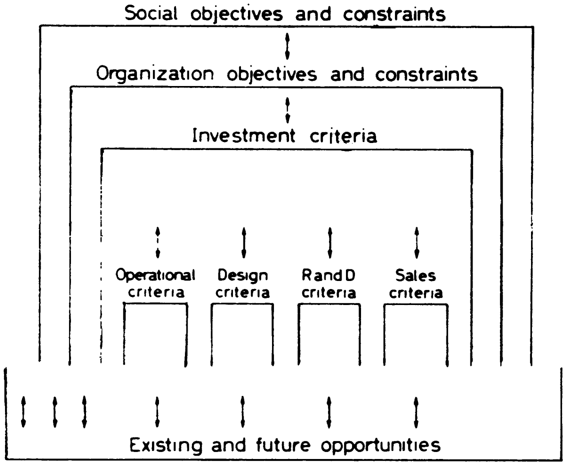


Figure 10.1. The open system of decisions

Any theory which is developed regarding decision has to be related to practical behaviour. Recently there has been a welcome growth in the empirical study of decision in design. At the same time there has been a growth in interest, an interest arising from different fields of study, concerning practical investment behaviour. Investment decisions and design decisions are linked together and with operational and research and development decisions as shown in *Figure 10.1.* As yet there has been no empirical observation of this overall theme, but in view of the interest of the subject, such work should be strongly encouraged.

Decision and Models

Any practical action in design almost inevitably involves the use of one or more models. These models may be most diverse in character and used either for solving a problem or for communication. If, for example, an opportunity is perceived, it has to be described by some model. If, again, there is a need to determine the distribution of stress within a component, this is calculated by the aid of a mathematical model. In each case it must be decided how applicable the model is to the given situation.

Within the practice of design there is concern with the exploitation of three kinds of model: the design method, the range of detailed problem-solving modes, and the models of specific technologies.

Chapter 11

THE ELEMENTS OF DESIGN

Ronald D. Watts

Introduction

An iconic model of a designer or design team Δ, as suggested in MESAROVIĆ (1964), is shown in *Figure 11.1.* Δ is in dynamic relationship with an environment ℰ, containing the total spectrum of scientific and technological knowledge (MCCRORY, 1963). A necessary, but not sufficient condition for a design process to eventuate is the existence of a valid human need evidenced by a communication *N*. Δ performs the processes of analysis, synthesis and evaluation leading to decision as shown exteriorized on the surface of Δ (JONES, 1963; ASIMOW, 1962; ALGER and HAYS, 1964). Decisions are represented by a line rather than by an area to indicate they are autonomic to Δ (STARR, 1963). Design proceeds by repeated cycling at a given level, until Δ obtains sufficient confidence upon evaluation to advance to a new level. In the main, progress is from a lower, more abstract, level to a higher, more concrete one: this is represented by the helical path on Δ. However, Δ learns during the process and frequently reiterates at one or more levels. A state function *D* of the design is associated with the process path and can be externalized as a set of statements at intersections of the path and the decision line. Various states of the design thus relate to the different levels. Asimow has given a two-dimensional flow diagram defining the processes at the different levels and the states as outcomes: this diagram is reproduced as *Figure 11.2,* and would be obtained by 'unwrapping' the design path from the cylinder of *Figure 11.1.* The design states (giving a vertical structure to the process) also proceed through analysis, synthesis of design concepts, evaluation of feasibility, later giving way to optimization, revision and communication.

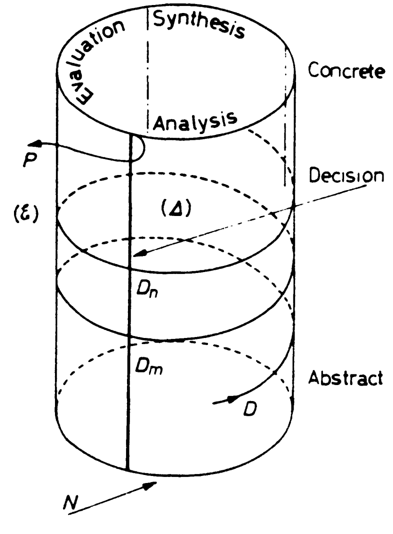


Figure 11.1. Designer Δ in environment ℰ

The process can be considered complete when Δ releases into ℰ a communication *P*, being a set of prescriptions for the embodiment of the design. The end to which *P* is a means is an artefact *A*: this possesses several functional attributes, some of which fulfil the need implied by *N*; others enhance the profits and reputation of Δ and his company, and yet others may have effects which are far-reaching into the socio-economic environment.

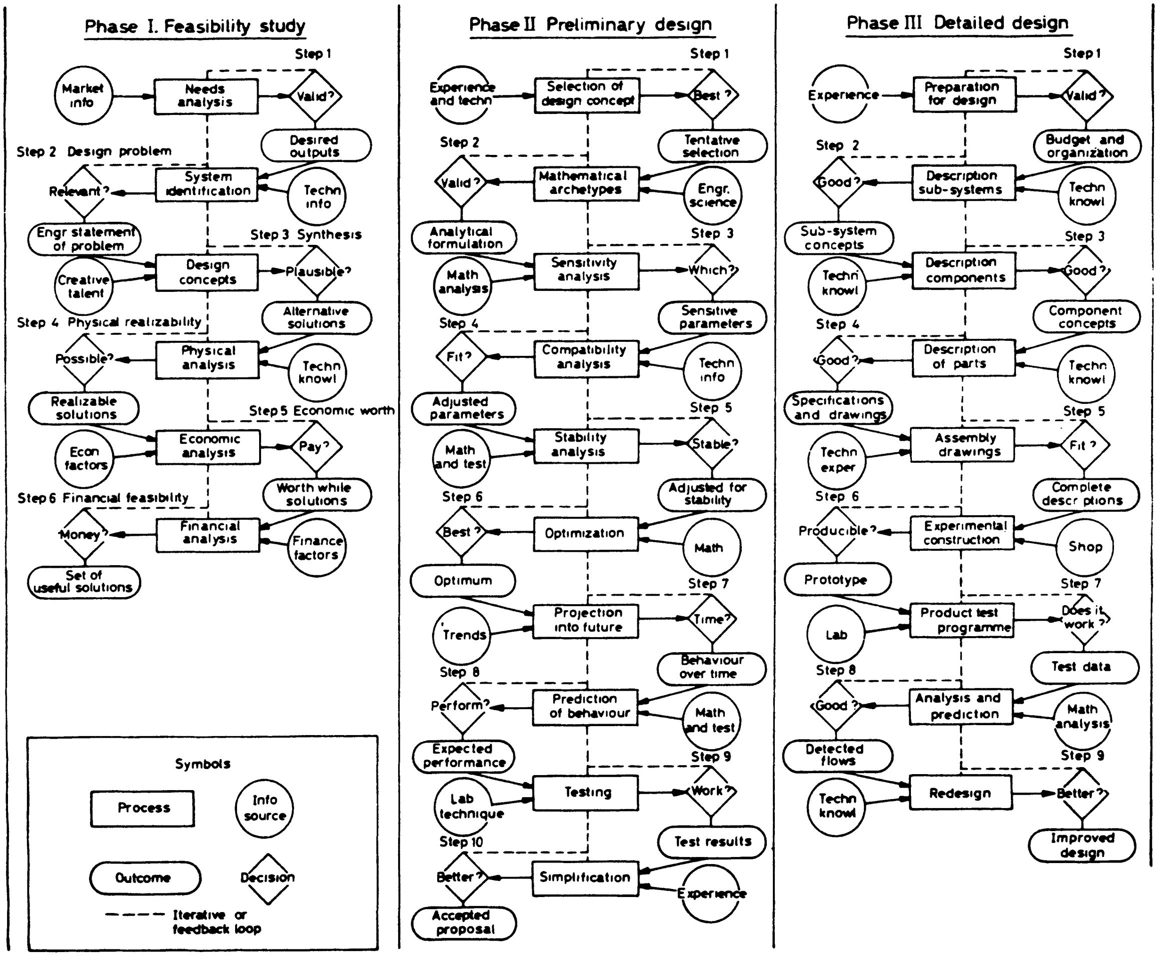


Figure 11.2. (From Asimow, by courtesy of Prentice-Hall)

The existence of N is thus symptomatic of a two-sided problem situation. On one side there are the factual causes giving rise to N which are the subjects S for definition, analysis, and measurement; on the other there are the implications of the proposed A which are the objects O for evaluation and decision. Intermediately are the requirements and resources of Δ and the company he represents: these together with S and O constitute a set of circumstances. The purpose of Δ is to achieve optimum conciliation of S and O in this set of circumstances. Failure to achieve optimum design often arises through failure to define the need problem situation adequately, or to evaluate well enough the implications of the chosen solution.

Analysis of the Need

The following comments are offered to emphasize the necessity for an objective analysis of the need and for caution against accepting statements of need at their face value. Sometimes N may be interpreted as evidence that a client is merely ignorant of an available device: in this event the need is considered not valid. Frequently a customer fails to appreciate or state his real requirements: *N* may refer to an artefact by name instead of by the function or service it is to perform, *e.g.* a 'voltmeter' may be called for when the need is to measure voltage. Taking into account the needs problem situation it is possible that a potentiometer would be required. A less trivial instance would arise if *N* referred to a house: is the functional requirement then *(i)* protection from the weather, or *(ii)* an instrument for living in as averred by Corbusier? Indeed it may be noted that *(ii)* does not exclude *(i)*, and in a needs analysis, Δ may well log weather protection as a design requirement and proceed to investigate the functions implied by *(ii)*. On occasion, *N* is presented as a comparatively tight specification rich in quantitative terms: this perhaps calls for the greatest scepticism on the part of Δ. Why are tolerances set to ± 1 and the panels inclined to 45°? It is not unknown for some well-meaning but ill-informed intermediary to close to costly limits the tolerances of fit of relatively unimportant parts to 'be on the safe side'; and if Δ does set the panels to 45°, ostensibly for ease in reading meter indications or manipulating controls, how is he to know that existing lighting will not thereby be reflected into the eyes of the operators?

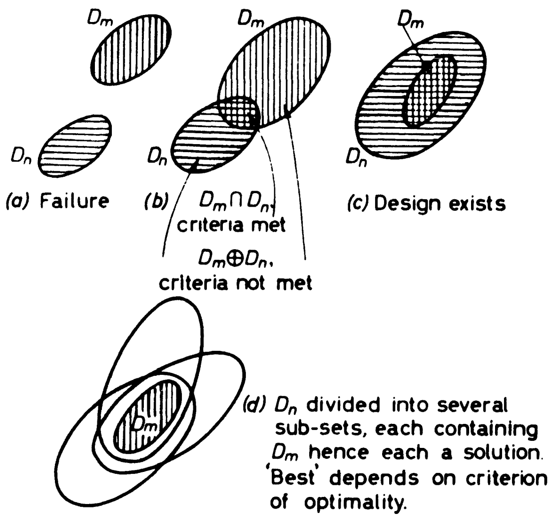
It is also necessary to appreciate that the needs situation changes with time: thus a continuous measurement of the market may be necessary in some instances if the innovations of today are not to become the bric-a-brac of tomorrow. In general, Δ must regard all the information received from $\mathscr{E}$ as time-varying and 'noisy': this refers to information about the needs situation as well as to scientific, technological, economic and other data. Δ acts as a perceptive filter, deciding what is and what is not relevant to the particular circumstance. Considerable reiterative probing into, and feedback from, $\mathscr{E}$ may be necessary before Δ decides to proceed.

Evolution of the Design and Documentation

In stating that the design states are describable by a set of statements, *e.g.*

$$D_m = \{d|d = \text{statement of design at the } m\text{th intersection}\}$$

the widest interpretation is to be given to the term 'statement'. For example, the description may assume the forms of verbal specifications, circuit diagrams, interaction diagrams, chemical formulae, mathematical models, indeed, any of the forms of written communication. The complexion of *D* changes as it progresses from *N* (where its elements *d* are sparse, general and predominantly qualitative) to *P* (where they are detailed, particular and richly quantitative). Any new *D*, say D_n, must imply any previous one, say D_m: hence $D_n \supset D_m$ is a condition for the design to exist; this entails there be no $d \in D$ which throws the design outside criteria specified by Δ. These criteria are written into *D* at the start: the function of the evaluator in Δ is then to apply the criteria when investigating relations on the union $D_m \cup D_n$. *Figure 11.3* shows the possibilities. Attention



(a) Failure *(b)* $D_m \cap D_n$, criteria met; $D_m \oplus D_n$, criteria not met *(c)* Design exists

(d) D_n divided into several sub-sets, each containing D_m hence each a solution. 'Best' depends on criterion of optimality.

Figure 11.3. *Variants of* $D_m \cup D_n$

is called to the fact that the boundary of D_n may be kept as wide as Δ is able: this is the policy of 'minimum commitment'. As an important instance in the evolution of design, adoption of this policy allows the requirements of a specification to be met whilst still giving room for manoeuvring among innovative, worthwhile solutions. One problem in designing is not so much what information is to be brought in from the outside world to be synthesized into a prescription, but rather, what information exists which the designer can afford to ignore or reject as irrelevant to the particular circumstance. The more knowledgeable Δ, and the richer the state of the relevant art, the greater the likelihood of the flourishing of a set of solutions from which the optimum can be selected.

It is evident that Δ is an information-processing agent seeking conciliatory relationships over a large set of elements, or factors, and that these change as the design progresses. Systematic book-keeping is necessary to provide:

(1) A means of keeping the goal in sight.

(2) A ready means of communication between all involved, especially so that decisions may be made 'with one mind'.

(3) A store of factual information.

(4) A store of propositional information.

(5) A record of decisions which may be of value in the post-design stage.

(6) An archival record of value to other design situations.

Jones, LATHAM (1965) and Alger and Hays give information upon this topic; attention is drawn to the last item. Choices often have to be made in design against non-metrizable qualities, for instance comfort, as criteria. If the decision, along with the processes giving rise to it, is recorded in one instance this constitutes a case history for a second occasion: at very least the probability is reduced of making the same mistake twice.

Approaches to Design

A logical approach is by envisioning the implication of P and of the resulting artefact A from its completion to its ultimate disposal. The embodiment of the design according to P ensures the fabrication of A. Questions therefore arise as to manufacturing resources: human (labour, *etc.*), physical (materials, machines, energy), informational (prescriptions, models, *etc.*), and economic. The fabrication of A ensures that it comprises a set of components which are logically assembled: this enforces the concept of system. A (closed) system is, by definition, a set of components or processes that can be bounded under the rule that all relevant interactions or interdependencies must be enclosed (Mesarović). Regarded as separate entities, each component has attributes, some of which make it of particular value to the circumstance (e.*g.* rigidity, resistivity, chemical inertness), and others of which are of nuisance value to the circumstance (e.*g.* weight, heat dissipation, cost). The mode of assembly of the chosen components is such as to exploit to advantage the desirable attributes of the components whilst minimizing the undesirable ones. It is the attributes of the components which are related by the mode of assembly. The characteristics of A, both desirable and undesirable, are determined by *(i)* the characteristics ζ of the components, and *(ii)* their mode T of interconnection.

(In terms of general systems theory, one refers to the ζ as the relational constituents and T as the structure, topology, or morphology of the system. One cites a set of relations such as R on A such that $R = \{ T, \zeta \}$. It is these relations which are investigated by Δ.)

Questions now arise as to the desired characteristics (outputs, functions, performances) of A since these give meaning to the expression 'exploit to advantage' in the foregoing paragraph. Questions also arise as to undesirable characteristics. Both sets of questions can be answered in part from an analysis of the needs situation. The totality of characteristics is obtained by considering the future probable history. The artefact will then be a labelled component interacting with others in a series of environments, *i.e.* A is a component of a series of systems: the processes it undergoes are predominantly out of the control of Δ. If for example A is a measuring instrument, the probable processes in order are: inspection, test, calibration, storage, packaging, transportation, installation, commissioning, operational usage, maintenance, repair, removal from service, disposal. Questions arise as to the possibility of vibration in transport destroying the calibration, the range of environmental temperatures in various usage sites and so forth. The interacting environments relevant to this example are again human, physical, informational and economic. Consideration of A in all its probable roles as a system component leads to sufficiency of specification.

An alternative approach is described by Jones. Given a statement N, each member in Δ compiles a random list of factors which he associates with N. The factors are serially listed (this formulates an initial set D). The list is communicated to all members who by constructive criticism, discussion and reference to information, make additions. The factors are then classified into categories which are suggested by the factors themselves. One category comprises ideas, solutions and propositions which are documented separately from other categories comprising factual information and design requirements. (A propositional set is thus separated from a factual set of factors for evaluation.) I suggest that reiteration of procedures sooner or later yields, for a given problem situation, the same or equivalent classifications and categories as other approaches.

Either of these approaches indicates areas where further information is required. Acquisition of information has been dealt with by Jones, and conditions for accurately establishing facts by LARRABEE (1945). ARCHER (1965) has devised a 'Systematic Method for Designers' providing a sequential list of activities to be performed and events to be recorded. The programme is set out in considerable detail, reiterative procedures

Table 11.1. Classification of Operational and Environmental Aspects

Usage	Influence	Existing resources
Occasion	Environment	Previous Designs
Duration	Safety	Existing equipment
Frequency	Policies	Services available
Sequence	Testing and installation	Experience
Operators	Time-scale	
Maintenance	Finance	
Personal acceptability	Manufacture	

Analysis on these lines has been described by Latham in PABLA (problem analysis by logical approach). *Table 11.1* is based on Chart C1 of his paper, and classifies the operational and environmental aspects under the categories, usage, influences and existing resources. GOSLING (1962) also proceeds on the basis of a prior concept of system.

Table 11.2. Morphology of Instrumentation

Definition: An instrument is a system which maintains functional relationships between prescribed variables.

Definition: Instrumentation relates to the design, construction and use of instruments for measurement and control.

Characteristics	Electrical	Mechanical	Mechanical	Fluid flow	Thermal	Chemical	Others	
Desired outputs Identify Quantify Resolution	Voltage v Current i	Velocity $\dot{x}$ Force f 3	Angular velocity $\dot{\phi}$ Torque T 3	Pressure p Flow rate $\dot{g}$	Temperature $\dot{\epsilon}$ Heat flow Q	μ $\dot{N}$	Across $\dot{x}$ Through $\dot{y}$	
Purposeful inputs Identify Quantify Resolution	v i	$\dot{x}$ f	$\dot{\phi}$ T	p $\dot{g}$	ϵ $\dot{Q}$	μ $\dot{N}$	$\dot{x}$ $\dot{y}$	
Uncontrolled inputs Amplitude Frequency	Electric field Magnetic field	Vibration Shock	Vibration Shock	Acoustic Pressure	Conduction Radiation	Corrosion Humidity		
Undesired outputs Identify								
Transfer properties	Gain	Response	Sensitiveness	Range	Error	Reproducibility Short term Long term	Damping	Bandwidth
Performance	Reliability	Maintainability	Durability	Safety				
Processes	Fabrication Usage	Calibration Ergonomics	Storage, etc.	Transportation	Installation	Amortization	Repair	Disposal

being specified at the appropriate stages of the design, and it is associated with a graphic network of the whole process. *Table 11.2* is a check-chart shown for use during the design of measuring and control instruments to ensure sufficiency of information.

Engineering Specification

Figure 11.4 shows an artefact (or system) *A* with its environmental connections, and suggests the formulation of an engineering specification to the following scheme. (A running example relevant to a frequency standard is appended.)

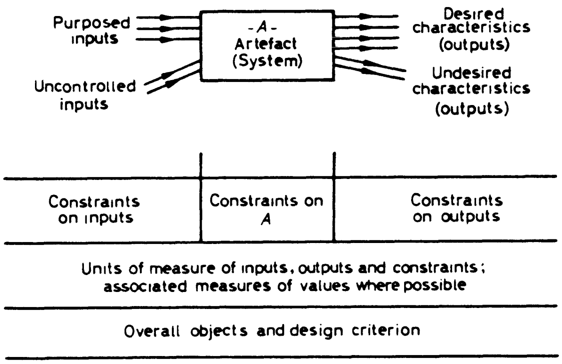


Figure 11.4. Artefact in its environment

(1) Desired Characteristics (outputs)
Continuous indication of passage of time: stability, 10^{-8} ; resolution, 1 sec.
Frequency outputs: 100 kc/s, 10 kc/s, 1 kc/s to 1 c/s with random access; each 4 V p–p; impedance ≯ 10 k ohm.
Record of error with respect to a British standard frequency transmission.

(2) Undesired Outputs
Heat, acoustic noise, electrical noise on voltage outputs, light reflections.

(3) Inputs
Purposeful
Physical (power, 240 V, 50 c/s floating battery).
Human (control, adjustment, maintenance).
Informational (standard frequency signals).
Economic (amortization, maintenance, depreciation).
Uncontrolled
Physical (ambient temperature range, 5 °–30 °C; vibration, mechanical, acoustic; dirty atmosphere; ambient lighting; human).

(4) Constraints on Outputs
Included in *(1)* and *(2)* above.

(5) Constraints on Inputs
Included in *(3)* above.

(6) Constraints on A
Size ≯ $x \times y \times z$; weight ≯ *p* cwt.
Expected service, 20 years.
Location as in Drawing 537.
Cost ≯ £100 per each sub-assembly.
Attention to ergonomics and aesthetics.

(7) Units of Measure
Included in above.

(8) Objective and Criterion
Demonstration of work of the department*.
Ratio of non-operative periods to total time.

In the example given, the location of the device is specified and hence it is possible to measure the environmental situation in respect of vibration, atmospheric pollution, lighting, In the event of a device being intended for use in a variety of locations, decisions would have to be made as to the nature and range of interfering imputs to be catered for.

Generation of Design Concepts

Design concepts can be generated using the notion of system: one seeks to maintain a relation (or set of relations) *R* by varying the relational constituents ζ whilst retaining the morphology *T*. The procedure has thus been termed the morphological approach.

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*The design and fabrication of this instrument formed a joint project for diploma students at the Royal College of Art (School of Industrial Design) and at the Northampton College of Advanced Technology (Instrumentation and Control Engineering Group).

The first step consists of recognizing that the proposed artefact A belongs to a class $\mathscr{C}$ of devices which have the same functional attribute R. Thus, if the design project is concerned with a device which indicates the passage of time as its characteristic, A belongs to the same class as watches, sundials, clocks and so forth. If A is a car, it belongs to the set of devices having the common property of transportation. In general $A \in \mathscr{C}$, where

$$\mathscr{C} = \{ Ai \mid Ai = \text{'has the characteristic R'} \}$$

The second step is to determine the relational constituents and morphology. This may be accomplished by posing the question as to what are common sub-systems (or processes) amongst all exemplars in the class. In the example of clocks, *etc.*, the essential sub-systems are a periodic oscillator, a means of indication, and an intermediate means.

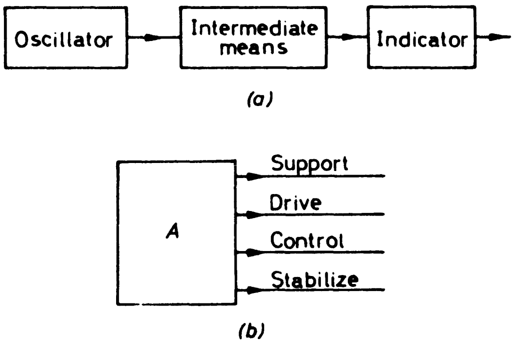


Figure 11.5. (a) A single-thread functional isomorph; (b) vehicle morphology

These are the characteristics which any device in this class 'must have'. The sequence in which these three sub-systems interact determines the morphology as shown in *Figure 11.5(a)*. The system of *Figure 11.5(a)* is the functional isomorph in all $A \in \mathscr{C}$.

One exemplar in this class might have been adopted for analysis. Thus a watch may be regarded as a 'single thread' (GOODE and MACHOL, 1957) system: the motion of the hands on the dial at the 'output' of the system may be traced back through intermediate gears to the balance wheel and escapement mechanism as the primary source of the motion. It would then be necessary to induce the general classes of oscillator, intermediate means, and indicator. Adopting the motor car as an exemplar in the class of vehicles, the dominant output is where the tyres interact with the environment at the road surface. The dynamic processes at the interface, are concerned with supporting, driving (propelling), controlling (steering) and stabilizing the car. These processes are seen to be necessary and functionally distinct: the morphology is as shown in *Figure 11.5(b)*. The processes need not be associative at one confined region of the interface, indeed they are not in an aeroplane. The difference between the two examples is that, in the case of the watch the object was analysed into major sub-systems, while in the latter case, the interactions of the object with its environment were analysed. Since A is always composed of sub-systems and is at the same time a system in an environment, both analyses may be carried out. For the watch, the analogous dynamic relationship to the road surface to tyre interface, is the ergonomic one between dial indication and human interpreter. For the car, one analogous single-thread system would be obtained by tracing back the steering motions from tyres to driver.

The third step consists of listing devices or processes with the same attributes as the constituents. The class of oscillators X_1 includes balance wheels, quartz crystal, tuning fork, magnetostriction oscillators, planetary, stellar, and atomic motions, body rhythms and so forth. A class X_2 of intermediate devices, and a class X_3 of indicators are also enumerated. Alternative means of support of vehicles are land, air, water, and so on. In general, several sets up to X_n may be formed but it is advisable to reduce the number as much as is consistent with carrying the concepts. Often these sets may be intuited thus obviating the formalization of the preceding steps: whether Δ can do this will depend upon experience and the object of analysis.

The fourth step is to combine members, one out of each set. When the morphology is thread-like, the order of combination is to be preserved. In set-theoretic terms, one forms the Cartesian set

$$X_1 \times X_2 \times X_3 \times \ \ldots\ldots\ X_n$$

which yields potential solutions as ordered *n*-tuples. If, to pursue the first example, the designer selects a transistor-maintained tuning fork, frequency-dividing circuits and dial indicator, he has a concept for a (once novel) watch.

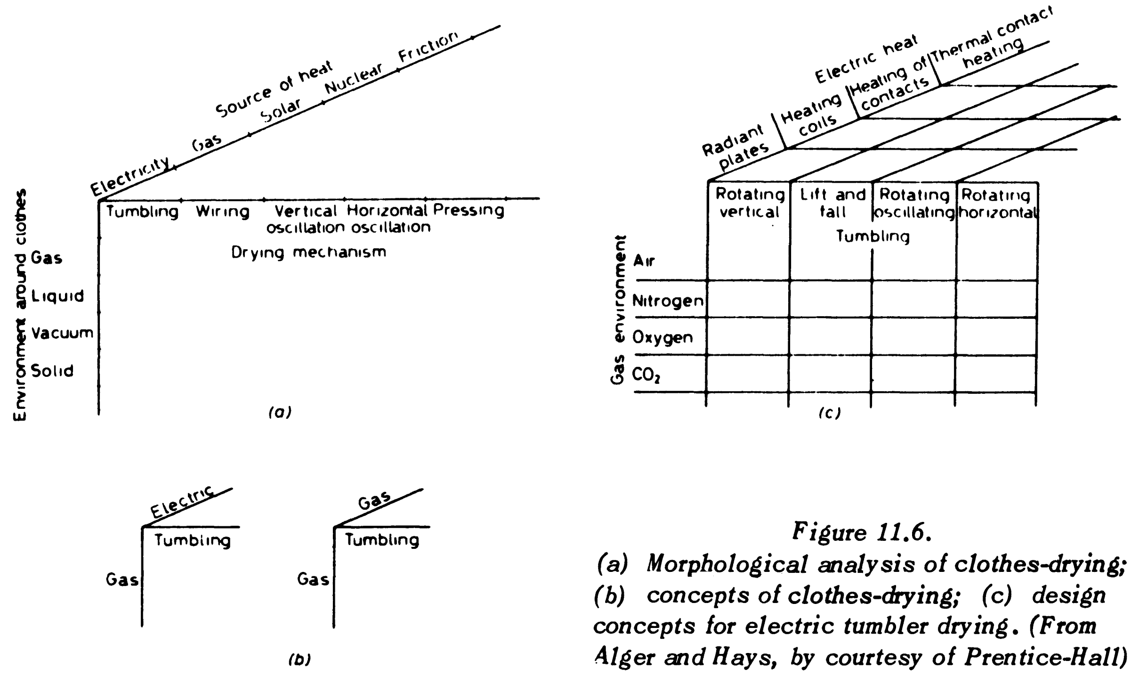


Figure 11.6.
(a) Morphological analysis of clothes-drying; (b) concepts of clothes-drying; (c) design concepts for electric tumbler drying. (From Alger and Hays, by courtesy of Prentice-Hall)

The morphological approach has been described in the literature. NORRIS (1963) gives an amusing and instructive example in which the specified function is to 'take the weight of one's feet': he recognizes the functional isomorph to be a simple spring-damper positioning device with load-spreading and cushioning members. The example of vehicle characteristics previously mentioned is taken from the same source. Alger and Hays describe a morphological analysis of clothes-drying as depicted in *Figure 11.6(a)*. The three dimensions of the model are equivalent to classes X_1, X_2 and X_3, with the various means of attainment as 'parameters' or 'values' defining the ranges of the dimensions. *Figure 11.6(b)* shows two concepts chosen for evaluation, and *Figure 11.6(c)* shows one of these being subjected to further analysis at a more detailed level of sub-systems.

The reason for suggesting that the number of sets should be reduced as far as possible can now be exposed: if selection of design concepts is to be carried out and one or more shown to be not feasible at a given level of generality they may be discarded at this level; Δ then has no need to proceed to more detailed level of analysis of those concepts.

Evaluation and Decision

The first phase of the design process is concerned with feasibility, and evaluation is directed to deciding which of the design concepts are capable of physical realization taking into account constraints of time and money. In later phases, evaluation is for the purposes of selection of optimum design, for ensuring stability, and in general for ensuring compatibility with the performance criteria relevant to the particular situation.

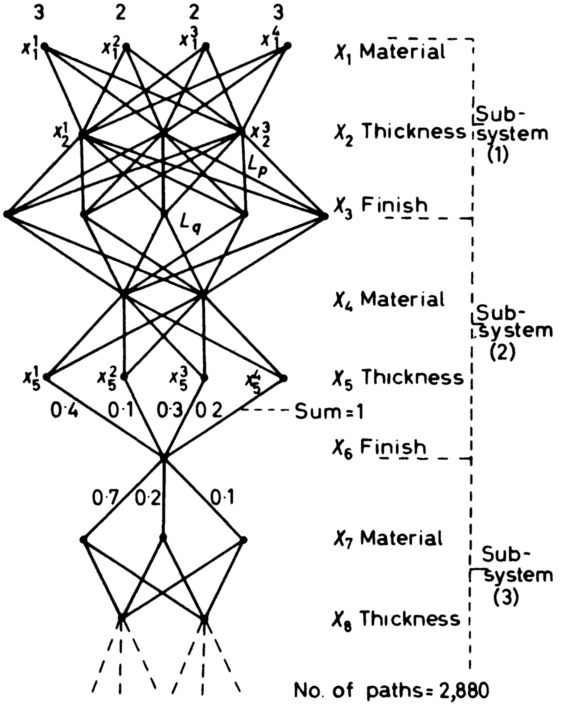


Figure 11.7. Design tree

It may be supposed that, by a morphological or intuitive technique, one of the required functional attributes is satisfied by any member x_1^n of a set X_1 of components, another by $x_2^n \in X_2$, and so on: by a component is here meant a technical means of attainment of the function. *Figure 11.7* shows a design tree formed of several such sets: to help fix ideas, but with some obvious loss of generality, names of components belonging to three sub-assemblies have been appended. Each link between two nodes represents a possible decision to use the combination of components represented by those nodes: any path through the tree thus represents a design strategy and Δ is to decide which of the available strategies meet the criteria, and ultimately which is the best one with respect to an optimizing criterion. The consequences of adopting any binary combination thus have to be compared with the consequences of adopting other combinations in the same 'row'. These consequences can be either advantageous or disadvantageous (with respect to performance criteria), and Δ seeks to assign values to the links by weighing the consequences. Decisions may be made upon comparison of the value products for the various paths through the tree. Link values are normalized so that they sum to unity in any one row to preserve proper comparison. As described, it has been assumed that Δ is indifferent to which of the x_1 components should be chosen: often Δ has preferences amongst the initial components and assigns values to these, afterwards incorporating them in the path-products.

In the general case, the number of links is unmanageably great and Δ is compelled to fragment the system: it is perhaps this activity which makes the most demands on the perceptive faculties of the designer. Some variables are relegated to the status of low relevance to the particular evaluation or the system is divided into sub-systems which are separately evaluated. Bearing in mind the definition of system, either method of fragmentation is not without its dangers: Δ may lose track of an advantageous interaction or interdependency or perhaps of a catastrophic one. For example, referring to *Figure 11.7* suppose sub-systems (1) and (2) are separated, and adoption of link L_p implies such rapid corrosion that a reliability criterion could not possibly be met, then a zero value would be assigned to L_p. Any path containing L_p must then necessarily have a path-product value of zero: it is as though this prospect had not been available in the first place. But now suppose that with link L_q of the connected tree, L_p implies cathodic protection, the interaction $L_p.L_q$ would probably be worth a value approaching unity. An analogous instance in the evaluation of propositional control systems is the necessity to recognize autonomous sub-systems for separation.

The weighing of relative advantages and disadvantages of selecting one link rather than another, poses problems of the relative importance of performance criteria: one solution may afford greater reliability at a greater cost, and another greater maintainability at less cost. The decisions here are concerned with solving further problems: for example, will the maintenance required if the second strategy be adopted cost more in the long run than if a more reliable but more expensive strategy be chosen in the first place? For Δ to come to an objective decision he must have access to case histories and invoke probability theory to arrive at a quantitative assessment for the particular circumstance: obviously maintenance labour costs on user sites is a factor of importance in relating maintainability to costs. However, this discussion stemmed from a consideration of link evaluation in a design tree: in general it may be expected that with each link are associated sub-problems requiring solutions and decisions and that these will vary from one design situation to another.

It has here been possible only to outline the kinds of activities which Δ undertakes as an evaluator and decision-maker. Evaluation implies measurement (FINKELSTEIN, 1963; CHURCHMAN and RATOOSH, 1959) *i.e.* the assignment of numbers to entities to express facts and conventions about them. If the designer is to be objective in his decisions he must necessarily refer to past history for bases of comparison: but the future is not beholden to the past and advances entail a probabilistic extrapolation. The results of past measurement lie in information of similar or equivalent prior systems, in experience, and in having evaluated a real model if the stakes are high. To extrapolate with the greatest chance of success suggests the use of decision and value theory, and of optimization and dynamic programming techniques (Mesarović; Asimow; Starr; Gosling; Goode and Machol; FISHBURN, 1964).

Acknowledgment

I wish to thank Mr. L. Bruce Archer, Director of Research, School of Industrial Design (Engineering), Royal College of Art, London, and also Mr. L. Finkelstein, Senior Lecturer in the Department of Production Technology and Control Engineering, Northampton College of Advanced Technology, London, for their encouragement and criticism.

Chapter 12

INFORMATION FOR DESIGN

J. Farradane

IN Chapter 11, Watts presents the need for a rational approach to the processes involved in engineering design as an intellectual activity. There is the morphological approach of NORRIS (1963) to provide a conscious framework (as opposed to intuition) of all steps in the design process. Parameters of essential qualities and quantities, and parameter steps of possible solutions for the requisite parameters, are identified so that the stages of identification, analysis and synthesis can be examined and systematically treated. JONES (1963) developed a more closely controlled logical approach for identifying factors and interactions of factors in stages which can be examined in matrix form through partial solutions to combined partial solutions and on to a final design. A system of logical analysis devised at the Atomic Weapons Research Establishment at Aldermaston shows a somewhat different logical system in which at any stage the problems are to be examined in the light of six basic elements: stage of achievement, place of operation, time factors, resources, methods of achievement of the design, and the justifications of the design. Considerations of methods of improvement are then to be applied at each stage. In the USA, MCCRORY, WILKINSON and FRINK (1963) have compared scientific research methods with the steps of determining need, need analysis, design conceptualization, determinations of feasibility, and final production.

It is thus clear that many people are striving to bring the complex and often apparently intuitional processes of design into sharper focus, so that the steps involved can be identified and formalized. Many of these processes are within the field of psychology: how people think and combine concepts, and how they solve problems. Difficult though such studies may be, there is evidence that the mechanisms of thinking are less complex than might be supposed. Such mechanisms are the means by which people manipulate concepts in relation to one another, a concept may be a single thing (as it is named) or a complex of things to which a single name can also be applied; the complexity of the concept does not alter the methods of handling it by human intellectual processes. The need is to be able to analyse a problem so that the concepts involved are clearly defined and capable of being brought into use, with due regard to their interrelations, in the subsequent stages of synthesis in solving the design problems.

Put into more everyday terms, these concepts are the items of scientific and technical knowledge which constitute the state of the art, the facts which must be taken into account such as materials data, and theoretical factors such as dynamic and static properties, and knowledge of processes, *etc.* At every stage of the design process, except perhaps that of the mathematics of optimization, adequate availability of the requisite information is essential. This information is to be found in the literature, the scientific and technical papers published in the journals, in data sheets, research reports, conference papers, *etc.*, and only too often unrecorded know-how of individuals or organizations. To obtain the recorded information it is necessary for the engineer to read, organize (classify) the knowledge obtained, and store it in a manner such that it can be retrieved when needed. The methods of storage and retrieval must also be suitable for converting previously unrecorded information into a retrievable form; this means that the methods must be able to handle detailed items of information, and not just books or bibliographies. Finally, there are the problems of isolating, understanding and perhaps formalizing the processes of synthesis in design; for an understanding of such problems at present only such methods as those of Jones' interaction matrices can be relied on to stimulate individual insight; further progress may depend on research on the psychology of creativity, but some lines of attack are becoming evident.

The first problem is therefore the availability of information. The engineer has tended to pay insufficient attention to the literature: partly because his traditional 'practical' approach has engendered a distrust of other work; partly because the lack, in many fields, of a growing body of unifying theory has made it difficult to see how much available knowledge fits into a pattern; and partly because of the emphasis often placed on the apparently overriding factors of local conditions and the possibilities of new materials. This encourages specious arguments to the effect that each design is essentially a new problem to which the literature cannot be adapted, that preliminary reading will prejudice creative thinking, and that theory is inferior to practice.

These attitudes are undoubtedly changing, but not fast enough to meet the demands of competition. Rapid technological advances are being made in all countries, and only an adequate knowledge of such work will provide the necessary basis for advance in Britain. It is only an accidental situation when practical progress is not based on sound theory. It is well recognized that engineering design is the spearhead of technological advance. Creativity is essentially a process of making new combinations of known pieces of knowledge; a new idea is not just imagined, it is produced by synthesis, or at least by analogy with known facts. The engineer *must* therefore become information-minded and demand adequate sources of information; otherwise he is dependent on the stock of knowledge acquired during his training or obtained by chance consultations with others. In other fields, notably chemistry, there has always been a traditional respect for the literature, for the avoidance of duplication of work, for the need to climb on the shoulders of others. Engineers have lacked an adequate number of fundamental journals and have instead had too many indifferent trade journals which tend to contain either low-level generalized articles or a plethora of snippets of information, all interspersed with an excess of advertisements. If an improvement is to be obtained, the demand must come from the engineer himself.

The individual cannot however be expected to survey any large range of original literature. What is needed is a comprehensive record of available information, and this is provided only by an abstracts journal. Unfortunately, engineering is even worse served in this respect. There is no comprehensive abstracting service in English; the *Technisches Zentralblatt*, in German, is fairly good. The *Engineering Index* is still far from complete and provides almost only the titles of papers, indexed under a large number of alphabetically arranged headings which, even with cross-references, are tedious to search unless the subject is quite straightforward. The *British Technology Index* covers some four hundred British journals, but is again an index (even though well permuted) and not an abstracts journal. Other abstracts journals cover, with varying efficiency, some specialized fields, for instance *Electrical Engineering Abstracts*, *Nuclear Science Abstracts, etc.* Compared with the comprehensiveness of *Chemical Abstracts* (which of course covers much chemical engineering), the resources at the disposal of the engineer are quite inadequate. The only remedy for this situation is for the engineers themselves, through their professional institutions, perhaps, to demand the necessary services; with sufficient demand the cost to the individual will not be too great.

If good abstracts are not yet possible, either for organizational or financial reasons, then at least greater attention should be paid to the use of data sheets and similar sources of information, as available, for instance, from the National Engineering Laboratory, the Royal Aeronautical Society, *etc.* Even these do not seem yet to be as generally used as they might be.

Assuming that the engineer has become 'information-conscious' and that an adequate amount of detailed information is being collected from all useful sources, both in this country and from abroad, the next stages are those of storage and arrangement so that as design requirements become clear it will be possible to retrieve any desired items from the store. The great increase in the amount of scientific and technical literature in recent years has led to the realization that the wastefulness and possible duplication of research if the knowledge cannot be recovered when needed is retarding progress; people speak of the 'literature explosion', though it is probably a matter more of the amount of knowledge available, in proportion to the number of people to whom it is useful, than of any sudden increase in the amount of knowledge or papers written. Two conferences with international support (in 1948 and 1958) have emphasized the problems of information retrieval. There are, basically, two requirements: how to analyse information reproducibly, and how to select relevant information accurately on demand. The first problem is that of semantic analysis and classification; the second that of using cognate methods to process a given question and obtain the required answer from the store. In the USA, there has been an exaggerated faith in the capacity of the computer to do both tasks, but the methods have not been strikingly successful. Many attempts have been based on the use of information as set out in written language; but researchers and technologists do not necessarily write well or clearly, and neither linguistic analysis (as attempted with computers) nor the mere selection of a group of single words (keywords or descriptors) whose subsequent conjunction in response to a similarly represented question is expected to impart meaning, can be considered adequate.

Even the simplest item of information is however more complex than the mere conjunction of isolated words. Meaning is present only in statements or other forms of *structured* information. The simplest representation of structure of this kind is to be found in methods of classification. The placing of terms in groups implies close relations between terms within one group, and other relations between higher and lower terms or between one group and another. The methods of morphological analysis of design problems, with subsequent steps of synthesis, are similar to those of the necessary analysis for classification and of recent methods of classification by synthesis, known as facet analysis. This method consists in analysing a subject field into a suitable number of groups (facets) whereby each group comprises terms or individual concepts with the same general character, *e.g.* materials, properties, processes, devices, theoretical concepts, and perhaps more general groupings (time, location, uses, *etc.*). There is no limit to the number of facets which may be established to cover a given subject field, but usually something between eight and twenty is sufficient. The headings may be made quite specific, *e.g.* raw materials, secondary materials, lubricants, *etc.*, intermediate products, testing equipment; separate facets may be made for more detailed distinctions, or these may be made separate parts of one facet as long as no illogicalities are introduced. A complex subject is then specified by citing the requisite terms from the facets, which have been arranged in a suitable order of successive subordination or other logical arrangement, and combining them in that predetermined order; with suitable coding of the facets, a unique classification code is produced for each complex required. The construction of the facets entails methods of analysis similar to those proposed by Jones for defining design factors. Facet analysis could do even more, since one could handle both materials and properties and also interaction factors, known partial solutions, *etc.*

The primary use of a classification of this kind will be to record the available information of all types. Thus there might be facets for materials (*e.g.* iron, steel, oil, plastics), static properties which could include shape and form (*e.g.* wire, tube, rod), dynamic properties (*e.g.* load, strain, stress, resilience, strength, stability), scientific properties (*e.g.* density, elasticity), mechanical processes, devices (*e.g.* bearings, cranks, shafts, valves, gears, screws, springs, condensers), theoretical concepts (*e.g.* fatigue, factors of safety, Poisson's ratio), and also perhaps a general facet to cover such terms as tolerances, standards, specifications, *etc.* It will be seen that the classification can be devised to fit any given set of requirements and will enable accurate classification to be achieved not only for objects, but also for complex devices, processes and more abstract types of information. The retrieval of desired information, by a similar process of coding the requirement and searching for a match, is a straightforward process. Such classifications have been found to work well within relatively restricted areas of knowledge. A good description will be found in a book by VICKERY (1960).

The identification of parameters and parameter steps in morphological analysis is equivalent to a second stage of faceted classification having more abstruse facets of design and performance specifications details, so that synthesized possible partial solutions can be compared with the coding of the general performance specifications. Such methods will not of course eliminate any of the intellectual steps of design, but could at each stage assist creativity by providing the facts in organized form, so that constant reference could be made to all known information.

Table 12.1. The Nine Categories of Relation

	Cognition	Temporary memory	Fixed memory or evaluation
Concurrence or recognition	Concurrence /Θ	Self-activity /*	Association /;
Not-distinct or convergent thinking	Equivalence /=	Dimensions States /+	Appurtenance /(
Distinct or divergent thinking	Distinctness /)	Reaction /-	Functional dependence /:

Increasing conceptual clarity ↓

Increasing associative memory →

The simple faceted method is not suitable for more complex fields where the subject matter covers different disciplines; in such areas, a concept of lesser importance in one context may acquire major importance in another context, and the synthesis of a complex item becomes too difficult. Research is now in progress by the author, and by another group, to discover new principles for dealing with more general fields. The facet principle is confined to arranging concepts initially as things, processes, abstract terms or properties, and distinguishing levels of complexity; such groupings then allow for the organization of levels (in a different dimension!) of class terms, and, in separate schedules, of heterogeneous group terms. Complex items of knowledge will again be produced by methods of synthesis, but this time with the insertion of specific relational signs between concepts (instead of relying upon a predetermined order to imply the relations). These relations have been derived from considerations of experimental work on the psychology of thinking, and it has been surprising that the categories of relations by which people construct (or synthesize) complex ideas are in fact relatively simple, only nine basic categories being required. These categories of relation derive from the interaction of three stages of mental memory and three stages of clarity of perception, as shown in *Table 12.1*.

The names suggested for the categories of relation are arbitrary, and the typewriter symbols (partly mnemonic) are for convenience in diagrammatic representations. The symbols can then be used between concepts to represent meaning in structured form (FARRADANE, 1963).

The relational symbols have ranges of meaning which may be *exemplified* (but not *defined*) as follows (*A* and *B* are in each case two concepts to be related):

/Θ *A*/Θ*B* can mean *A* in the presence of *B*, or *A* in the bibliographical form of *B* (*e.g.* engineering dictionary)

/* *A*/* *B* expresses intransitive activities (*e.g.* man walking, bridge collapsing, lamp shining)

/; *A*/; *B* expresses an indirect or abstract property *B* of the process *A* (*e.g.* design symmetry), or the agent *B* of the process *A* (*e.g.* compression with a piston)

/= *A*/= *B* expresses some degree of equivalence, up to full synonymity, or the application of the concept *A* as the concept *B* (*e.g.* a fuel cell as a power source)

/+ *A*/+ *B* expresses the position in time or space (*e.g.* *A* is at a given time or place or position *B*), or the state *B* of *A* (*e.g.* a salt in solution, a metal at a given temperature, a plate with a positive electrical charge)

/(*A*/(*B* expresses that *B* is a physical property of, or part of, the concept *A* (*e.g.* steel strength, stator winding)

/) *A*/) *B* expresses the distinctness of *B* from *A*, as in the case of substitutes, imitations, *etc.* (This relation is rarely needed)

/- *A*/- *B* expresses any action of *B* (a process or thing) on *A* (*e.g.* plastic subject to moulding, lever acted upon by a spring)

/: *A*/: *B* expresses *A* causes *B*, or *B* arises out of *A* (*e.g.* fatigue causing fracture)

It is thereby possible to write any complex statement or subject in diagrammatic form with concepts interlinked by the relations. The result may be simple linear representation, or branching or circular structures. There is psychological evidence that the mind does not deal with more than at most four relations of one concept with other concepts, under normal circumstances, and this means that a two-dimensional network pictured on paper is adequate for delineating even complex subjects. In diagrams, a relation set vertically between two concept words implies that the upper word is in the *A* position to the lower word (*B* position) as in the examples of relational meanings given above.

A straightforward example would be ‘apparatus for fatigue testing of 7075-T6 aluminium alloy in vacuum’, which is analysed as in *(1)* below (note that logically it is the alloy which is in vacuo, not the testing, and that fatigue is an indirect and not a normal physical property).

A more complex example would be 'comparison of fixed-bed and fluidized-bed heat exchangers for utilization of the low-potential heat of waste gases', which is analysed as in *(2)* below.

The actual terms used would of course be drawn from the pre-established classification, and coded as desired. For retrieval of desired information from the material stored, the enquiry would be coded and a match sought; the enquiry might prove to be part of a more complex subject stored, or *vice versa.* It should be possible to extend the search by 'browsing' at any point for higher or lower generic terms, or cognate terms, if the initial search did not produce exact results. Rules are also being sought for equivalents of condensations of meaning or logical jumps such as are often found in the way questions are asked, since less important terms in a statement tend to be omitted.

The design process, after need has been established and the requirements have been analysed as far as possible, then consists of a series of steps or levels of synthesis and evaluation. At each step, information is required, the type of information becoming more complex as the processes of synthesis of design proceed. The storage of the simplest information (*e.g.* properties of materials) may be satisfactory in the form of alphabetical ordering of data sheets; if the possible range of say devices (*e.g.* gears, heat measuring devices, *etc.*) is not initially known, then a classification system must be available for consultation; this classification may be the same as that used for controlling concepts for the more complex methods of analysis and recording of information, as described above. In the examples analysed above, the information store will enable this (and no doubt other) type of fatigue testing apparatus, or heat exchanger, to be located (in a paper) for information. At higher stages of design synthesis the types of information, though more complex, will still be analysable, and storable, by the relational indexing method. It is possible also to introduce numerical data into these analyses, to some extent.

A more sophisticated application of the classification is also possible. Where a given desired item of information is found not to exist among the stored records, a close parallel, which may suggest a useful alternative, may perhaps be located by changing one concept at a time in the structured analysis of the information required, the change being to a higher or lower generic term or to a cognate term, and repeating the search. Organization of the store of information on a computer will of course enable various types of search to be made very rapidly.

The need for information does not however stop at the primary stage of initially available knowledge, or state of the art. The stages of synthesis of a design will successively reveal complexes of various sorts whose compatibility of components and feasibility need examination; the existence of previous work on such complexes or on nearly similar or analogous situations must also be traced, if possible, so as to save duplication of effort. Only a highly sensitive method of analysing and storing information

(1) Aluminium/:Alloy 7075-T6/; Fatigue/-Testing/; Apparatus
/+
Vacuum

(2) Gases/;Heat/;Potential, low
/= /-
Waste Utilization/+ Heat Exchangers/; Fixed-bed
Fluidized-bed } /-Comparison

will cope with these more complex situations.

There is furthermore the possibility that the methods of analysis of information may be adaptable to simulating steps of synthesis, at least for early stages. Research is at present being envisaged to establish rules, on the basis of psychological investigation in the field of decision making, problem solving or logical reasoning, for combining two known items of information. Thus if a piece of information analysable as *A/B/C* (*i.e.* the terms *A*, *B* and *C* in some relational structure) is known and if *C/D/E* is also known, then rules for combining them will be sought, for example as *A/B/C/D/E* or in some other way according to the relations involved. This would be equivalent, eventually, to a new mathematic 'logic' of induction or creativity, It might be possible to show quite simply whether devices or processes were compatible.

To conclude, therefore, the problems of the design process are those of creativity in general; a formalization of the creative task can be achieved only by understanding and imitating mental mechanisms. This assumes the adequate exploitation of available information; full awareness of the need to obtain, store, retrieve and use existing information is therefore essential.

Chapter 13

PATTERNS

A.D. Newman

Introduction

A design could be said to be a pattern created by man, with the purpose of meeting some specified requirement; such purpose, perhaps, being aesthetic, as in artistic designs, or severely practical, as in the case of the logic of a digital computer – or a combination of the two, as is the case in architecture. But whatever the requirement a design is essentially the result of a creative act.

Since a design is a special class of pattern, there is relevance in speculating on the nature of the pattern. It is a recursive thing, a hierarchical thing. Any pattern in general is built from other, lesser, patterns, each having a relationship with each other. A relationship itself has something to do with structure and is surely highly restrictive. The final judgment, for example, on the distinction between a meaningless set of marks and a pattern is the prerogative of man, so evidently the relationships in the structure of a pattern are in some ways an analogue of human thought processes. Hence one passes from design to pattern, and from pattern to thought processes.

Thought Processes

CHOMSKY, in his latest (1959) approaches to an understanding of the grammar of human language, makes the obvious yet profound reflection that speech is clearly the most obvious pointer to the nature of thought – much more so than written communication. Speech is essentially serial and would appear to be the kind of structure known as a process. Such a process is related to modern graph theory and again to modern computer programmes.

Computer Programmes as Graph Nets

Now a computer programme can be looked upon as a graph of a special sort. In general it consists of a number of 'node' points linked by directed connectivities. Usually in a computer programme most nodes are connected *only to a pair* of others: one by a connection to it and one by a connection away from it. But always some nodes have several others directed to them, and some, two directed away from them. This is shown in *Figure 13.1*. Here the network is active and sequential. At any one step one node is active; at the next step this node activates the node to which it directs. Where a node points to two nodes, only one is chosen to be active at the next step, the choice depending upon certain conditions.

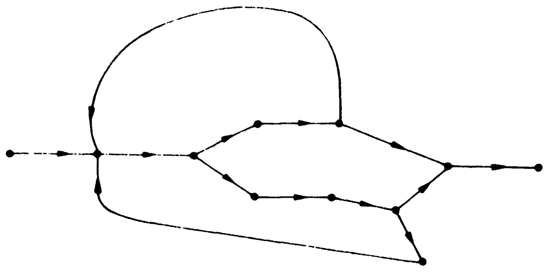


Figure 13.1

Another setting of the programme net is shown in *Figure 13.2*. When a node such as *A* is active, information passes through it to a store, either directly from a store or from several stores via some sort of computing device. A node such as *B* is vitally different. In this case no information passes but the next activated node is either *X* or *Y* dependent on the

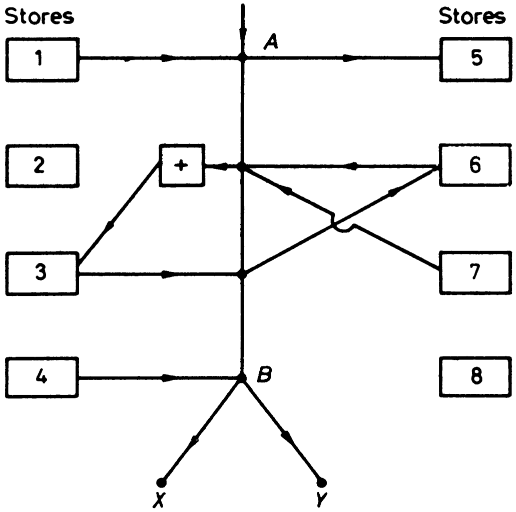


Figure 13.2

nature of the information reaching the node from some other store. Four points should be noted:

(1) It is not essential for only one node to be active at a time.

(2) The number of paths 'fanning in' to a node or 'fanning out' from it need not be limited to two.

(3) The important kind of node is the kind called *B* in the diagram – *i.e.* a node which when active leads to one or several, according to the input criteria.

(4) It is not necessary to have the 'double' network.

An active graph net can be designed with connections of more than one kind which can undertake any possible computing task. In this case the information storage, the programme, and the computation are all one entity. *Figure 13.3* shows such a system. In this the connectivities are +1, -1, and +½. A node becomes active if the sum of the connectivities from active nodes is 1 or greater. If the *A*'s and the *B*'s are made active according to two 3-digit binary numbers, then, in due course, (actually eight steps later) the *S*'s will become active according to their sum. Thus, if the starting states are

$$A_1 = 0, \quad A_2 = 1, \quad A_3 = 1$$

$$B_1 = 1, \quad B_2 = 1, \quad B_3 = 0$$

the final *S* states will be

$$S_1 = 1, \quad S_2 = 0, \quad S_3 = 0, \quad S_4 = 1$$

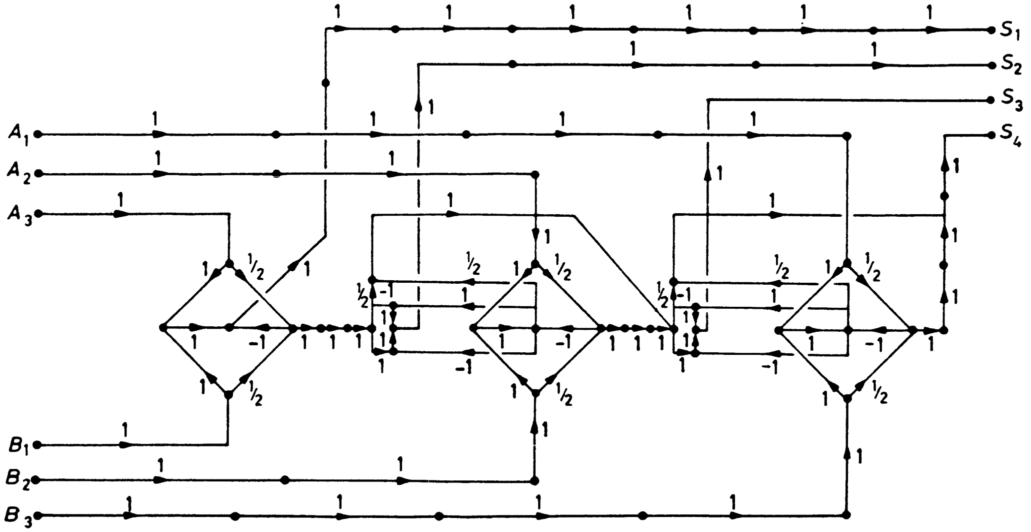


Figure 13.3

Although different things occur if other nodes are made active as starting nodes, the processes which occur as the result of activity in this net are always closely related to addition.

The net of *Figure 13.3* is not recursive, but there is no reason why S_1, S_2 and S_3, for example, could not lead to A_1, A_2 and A_3, and it is possible to have a system in which any node, in general via several others, points to every node in the network. In such a case a given activity state can be the result of a considerable range of input states. On the other hand, since the effect of an input pattern to the system will be dependent upon its activity state within the network at the time of input, a wide range of output activities could be produced by a given input, depending upon context.

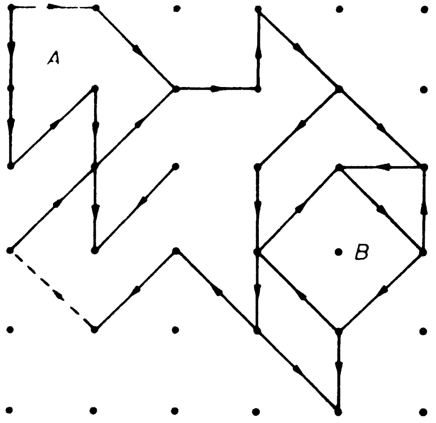


Figure 13.4

The net of *Figure 13.4* clearly has two parts, *A* and *B*. Within *A* or *B* there is heavy interconnection, but there is a loose *A* to *B* connection. If the dotted link were made there would be loose *A* to *B* and *B* to *A* connections. Active graphs representing meaningful procedures break up in this way. In practice there can be a hierarchy of steadily larger groups, the connections becoming progressively more tenuous.

The Concept of Meaning

The concept of 'meaning' may now be examined in terms of the net programme. Clearly, man carries out procedures, and it could be supposed that he does this by means of interconnected neurones as nodes in a programme net of the sort discussed above. If this were the case, the programmed procedures would be determined by the directions and strength of the connectivities. Learning a new procedure would be done by making new sets of connectivities, and procedures adapted to new purposes by adding or modifying a few connections only. It would be expected that in a living creature a number of straightforward separate procedures would be developed first, but as time passed these would become more knotted and interconnected, and links would occur between the knots. Thus the output states produced by activity of input nodes would depend more and more on the activity of internal nodes and hence on the content in which the input occurred.

Now it is not necessarily implied that the brain actually operates in the manner of this system, but it is suggested that the system's behaviour is such as to allow reasonable speculations about concepts such as meaning and likeness.

All the nodes in a tightly interlinked recursive part of an active net are very much of a definite whole. Together they constitute an entity closely analogous to the Jungian idea of a complex – in a sense a tightly knitted part of a net constitutes a 'concept'. The 'meaning' of a given input set can, in this model, be looked upon as the complex with which the set is directly associated. But in a real sense this depends not only on the position of the initially activated nodes in the general net, but also on the state of activation within the net at the time of input.

In this way, meaning is not absolute. It depends on the net and the relationship of the inputs to the net which in turn depends upon the experience and the general context in which the stimulus occurs. Meaning therefore becomes a private thing, an ephemeral thing, and communication between men and their colleagues relies upon basic similarities between different men and their past experiences. Likeness can be looked upon in a similar way, for two input nets can be said to be similar if they communicate with largely common parts of the net.

Output sets can be defined in an analogous way. Looked at thus, 'likenesses' depend very much on context, and are again essentially 'private'. Likeness, like beauty, is in the eye of the beholder, and the eye changes continuously.

If a pattern must essentially be meaningful, it follows that what is a pattern to one man may be a meaningless jumble to another, or perhaps even to the first man in a different time or in a different context. It is perhaps because of this that any new form of art tends to be 'meaningless' or incomprehensible to people who have not followed the developments that led to it. Any pattern that is created as the output of a net programme is evidently closely related to the structure of the net, and hence very heavily restricted in possible form. Even so, the total number of output patterns that can be produced from a stable, active, net containing 10^{11} nodes and several orders more of connectivity, is immense. If the connectivities evolve (change with time) the possible output variation is even more tremendous.

Thus even if the 10^{11} neurones of the brain formed a stable set, the brain would be able to produce a great many behaviours, and it would be virtually impossible for its activity during two different periods to be identical; thus any pattern produced by such a system is truly a 'creation'. In another sense, however, it is *not* new in that it has arisen almost entirely out of past experience. A little thought shows that, looked upon from the point of view of a structures procedure, the patterns of many designs are remarkably similar. Thus a design for a hydraulic system will be found to have a very close parallel on the one hand to some mechanical system, and on the other to some electronic system. It would also seem that the invention of a remarkable new design will be found to have introduced a very small, though vitally important, change into a previous system. Design can, perhaps, only be truly carried out by analogy.

The Tasks of Realization

The above ideas suggest the ways in which design could perhaps ultimately be carried out by a machine. It was suggested earlier that a design is a pattern having the purpose of meeting some specified requirement. Since the requirement is man-specified it will have a structure and can be further specified in the form of a programme process. Once this has been done, the design is in a sense complete. The problem then is how to specify requirements in the form of a programmed process, and arises from the fact that the specification will not be given in the form of the structures, but rather in the form of words or drawings which, as input to, or output from, the net are tightly linked to certain complexes, and which therefore label or represent the complexes. The actual designer, whether man or machine, is beaten from the start if its make-up of experience does not contain similar complexes 'labelled' in a similar way.

The next thing is to discover whether the various sub-structures can exist meaningfully together – that is to say whether they are linked, or can be linked in a way analogous to the designer's thought-structure net. This can be discovered in one of two ways, either by experimenting with context, or by a small evolution in the thought-structure net. Either way, of course, calls for a degree of random change. But if the design pattern is worked out as a hierarchy, the required design will involve perhaps a small rearrangement of concepts or complexes already existing in the designer's thought-structure, and at most small changes in the sub-patterns. Design is possible in a reasonable time simply because the required amount of trial and error is very small, and only possible for a designer with a thought-structure adequately developed as a result of a suitable experience.

Where the purpose of the design is to please aesthetically, different problems arise. For instance, the design must be meaningful to the observer, and must thus match the structure of his thought processes. Clearly it must do more. As a conclusion, a postulate about this 'more' is considered.

The Aesthetic Postulate

The brain is frequently thought of as a device essentially to match motor or autonomic activity correctly to the stimulus. Correctly, in this context, means 'in a way conducive to survival'. This in turn is related to correct body functioning, which once again is measured in terms of activity in the autonomic nervous system.

A sensible way to design a brain therefore would be to make adaptation of net structure dependent upon information received from the autonomic system. The most obvious and pressing information would clearly come from damage occurring to the outer structure of the body – this, of course, is pain. Other information reaches the brain from the autonomic system bringing news of more subtle alarms. In addition the brain needs information that 'all is well' and that a given problem is being solved. What would be the best measure of 'all being well'? Surely a lack of nodal activity in an alert brain. Thus it would seem plausible that any pattern which was not only meaningful in matching thought processes, but also was of such a nature that it minimized nodal activity would be 'pleasing' to observe. If this were so, beauty would truly be in the eye of the beholder, for appreciation would depend basically upon the actual thought-structure.

Chapter 14

CREATIVITY

Geoffrey H. Broadbent

Introduction

The inherent difficulty of heuristics, the study of design method, is that one becomes fascinated by means, rather than with ends. One tends to think of 'problem-solving' instead of 'design' and to concern oneself with rational procedures instead of creative acts. All design processes are based on scientific method. For some time now, the aim has been to devise rationalized procedures analogous to the mathematician's algorithm, sets of instructions for solving particular problem types which require no access of creative thinking whatsoever. Some theorists such as DAVIS (1958) have suggested that if no such algorithm exists, then the problem is unsolvable. As GOSLING (1963) has pointed out, design methods have their vogue and then fall from esteem. If they really are of value, their development is continued into a specialized branch of knowledge, which will then be useful in the understanding of particular classes of problems.

As such a vogue recedes, others advance to take its place, and recently there has been an increasing emphasis on human values in design. In part, at least, this has been encouraged by Operational Research (OR), a discipline which is complementary to the Systems Engineering which Gosling advocated. Both are concerned with the design of systems in which human operators will control machines, but OR concentrates on the analysis of activities and procedures; therefore it places particular value on the contribution of the human operator. Yet on the whole, OR is concerned more with the improvement of existing systems than with the design of new ones (ACKOFF, 1961). It will therefore be appropriate for certain classes of design problem, as systems engineering will be for certain others, but neither will be particularly effective when innovation is required.

On the whole, design methodology has tended to shy away from innovation. It is comparatively easy to devise a design process which will lead to the optimization of accepted methods, but innovation involves uncertainty, and therefore seems less amenable to systematization. There are other reasons too for resistance to innovation. It implies threats to security, often in very real terms – earning capacity, established working patterns, even the jobs of those who are resisting change. Naturally, if they have helped to develop existing systems, and this includes rationalized design procedures, they do not wish to see them superseded, with consequent loss to themselves of prestige, status and recognition.

Creativity in Design Method

Yet it seems to me that current design methods are less efficient than they might be, because they fail to build in the 'unreliability' of the human operator, which is the only real source of creative ideas, good and bad. The most important innovations in the history of ideas and inventions have been achieved, on the whole, by an access of creative thinking into some version of scientific method. It should therefore be possible to devise further types of design process, additional to systems engineering and OR, like them akin to scientific method, but which will have built-in mechanisms to encourage creative innovation, where this would be appropriate.

If DEWEY'S classic analysis of scientific method is taken, and broken down into its constituent parts, the following five steps are obtained:

(1) The occurrence of a difficulty.

(2) Definition of the difficulty.

(3) Occurrence of a suggested explanation or possible solution.

(4) The rational elaboration of an idea.

(5) Corroboration of an idea and formulation of a concluding belief.

Dewey was concerned with an analysis of the complete act of thought and, often, he has been misrepresented as advocating a totally rational approach to the subject. But he is careful to point out that his third step, explanation or solution, is a matter of inference, which involves 'a leap, a jump the propriety of which cannot be absolutely warranted in advance'.

In OR terms (as in Ackoff), the parts of an operation are designated as 'black boxes'. OR is not particularly concerned with the contents of these boxes, but by thinking of Dewey's method in operational terms, the types of black box which will be appropriate for each step can be defined. Steps *(2)*, *(4)* and *(5)* clearly are strictly rational. The most efficient device available for operating rational processes is the computer, which will be entirely appropriate for these steps. But step *(3)*, according to Dewey is irrational, and therefore it requires a different type of black box. It is precisely the ways in which the human brain differs from the computer which make it the most effective device for use at this stage. In terms of learning capacity, memory, predictability and the operation of an algorithm, the computer can always be made more efficient than the brain. But the brain will be superior whenever value judgments, form recognition, association of ideas and the generation of unpredictable relationships are concerned (WALTER, 1953). In other words, the most effective design process will utilize the brain and the computer, working together in a symbiotic relationship, each acting in ways which are not accessible to the other. And provided that steps *(4)* and *(5)*, rational elaboration and corroboration, are carried out with the utmost analytical rigour, it will be an advantage if step *(3)*, the creative leap, can be as wild and imaginative as possible.

Creativity in Art and Science

There is an extensive literature on the subject of creativity in art and science, which traces the ways in which the mind prepares itself for this leap (see GHISELIN, 1952). WALLAS (1926) outlines four stages in his *Art of Thought*: preparation, incubation, illumination and verification. In the preparation stage, the brain is programmed with all the facts relevant to the problem – these, of course, will be available to the brain from the computer after Dewey's step *(2)*. Once the facts have been assimilated, the problem is dismissed from the forefront of the mind, and incubation takes place at an unconscious level. During this period, one will be engaged in a variety of other activities, mental and physical. At times, of course, the problem may emerge into the conscious mind again, or into a threshold state between consciousness and subconsciousness; one will be thinking about and around it, but the creative 'leap' may occur unexpectedly at any time. Illumination, in fact, is likely to strike at an unguarded moment, when mind and body are completely relaxed. This fact is confirmed in many famous accounts, such as those of Poincaré, Gauss, Mozart and Helmholtz (HADAMARD, 1949). After the leap, of course, the solution is subjected to rigorous analysis and verification by experimental test.

These stages are common to artists and scientists; the great creative acts which have shaped the twentieth century, and given contemporary culture its unique flavour certainly have them in common. I take these to be the discoveries of Relativity, Cubism and the 12-note Method in music.

Einstein's struggle is well documented (see, for example, WERTHEIMER, 1945). He worried for six years and more – not over the solution to his problem, but over the actual nature of the problem itself, which was how to reconcile Newtonian mechanics with Maxwell's field theories. At an intermediate stage, during incubation, he realized that 'light is the key', and then finally, in the seventh year, the flash came when he understood that time is the fourth dimension. After this, the rational elaboration of his idea took only five weeks, and the experimental verification was left to others.

There are curious parallels in the discovery of Cubism, not least in the fact that, at an intuitive level, the painters also were concerned with a fourth dimension (BARR, 1933). After years of imbibing 'influences' from the entire history of art, they realized, during the incubation phase, that Cézanne was the key – and then the flash came when, for the first time, Braque was confronted with Picasso's *Demoiselles d'Avignon*. He saw that a painting need not look like anything at all, but could be a completely new thing in its own right (COOPER, 1956). So the Cubists began their tremendous exploration into the nature of visual reality; the rational elaboration of their idea took about a year, and its validity has been corroborated in the history of the visual arts ever since.

The musical equivalent followed a similar pattern. Composers such as Wagner and Debussy had been breaking down the old tonal system and Arnold Schoenberg realized that there were inherent difficulties in writing music in no key at all. For six years or so, he stopped composing altogether, letting the problem incubate, and then, in 1923, he wrote a little piano piece in which a basic row of twelve notes is repeated in various ways, but always in the same order (STUCKENSCHMIDT, 1959). 'I believe', he wrote 'that I have found a key' (STEIN, 1964). The flash again, and significantly enough, Schoenberg's flash is analogous to Einstein's, for he says (1950): 'The two-or-more dimensional space in which musical ideas are presented is a unit.' The manner in which Schoenberg devised his Method is an object lesson to anyone who is engaged in the methodology of design. There was no question of deriving an algorithm for composing music; Schoenberg wrote intuitively, with conscious avoidance of the tonal system, and then analysed what he had done. Only then did he devise a set of rules for composition, and their validity has been proved since by the crucial effect the Method has had on the development of music in our time.

It may be argued that these epoch-making discoveries in Physics, Painting and Music have little to do with everyday activities in design, that their authors were different in kind from everyday designers. That may be true, certainly one doubts that Einstein, Braque or Schoenberg needed a systematic design method in rationalized terms. However, the use of computers in design can raise the efficiency at Dewey's steps *(2)*, *(4)* and *(5)* to such levels that, if a balanced operation is to be achieved, the creative leap at step *(3)* must be made equally effective.

Creative Techniques

Many techniques are available for enhancing creative capacity. One tends to view them with suspicion because they derive from the advertising industry and savour too much of a Madison Avenue approach. BAKER'S *Your Key to Creative Thinking* is full of practical tips in ideas-generation, but the examples he quotes, such as formulating a detergent of two-colour granules, packaging it in different ways for different purposes and selling it with gift offers, are precisely the techniques one has learned to distrust from, say PACKARD'S *The Hidden Persuaders*.

The psychology of creativity is not as helpful as it might be either, because it tends to be theoretical rather than pragmatic. The standard tests on creativity hardly ring true with those who are engaged from day to day in creative activity. Typical tests, as listed by HYMAN (1963) take a form such as: 'How many definitions can you give for the word "bolt"?' or 'List all the uses you can for 5,000 used red bricks.' Other tests might involve the relationships of simple geometrical shapes, the completion of a story in certain ways, or problems in numerical manipulation (GETZELS and JACKSON, 1962). Several experimenters have claimed, according to Hyman, that on test, people who were told to 'be creative' performed as well as those who had been educated to it. This seems to me inevitable when the tests themselves are concerned largely with ingenuity, which I take to be only one component of creativity.

In fact, a clear definition of what the creative act comprises, in terms of mental processes, is lacking. Three views are held generally in psychology each of which may represent a part of the truth. The first of these is the Determinist view that thinking is a matter of logic, concerned with the progressive alternation of hypothesis and test. In its developed, Renaissance form, this is the basis of scientific method: gather the facts, observe relations between them, formulate assumptions and test them. Much thinking in the field of design method up to now has been rigidly determinist, and therefore it has excluded the possibility of more sophisticated techniques. The early psychologists added to determinism the Associationist view of stimulus and response. They believed that ideas are associated in the mind when they first arise, and that the creative act consists of drawing on these associations in rapid sequences of trials and errors. RUGG (1963) states that Dewey's aim initially was to reconcile these two different approaches.

Both the determinist and the associationist views on creativity were criticized severely by Wertheimer in his formulation of Gestalt psychology, based on the concept of structurization. In Gestalt theory, a problem consists of an incomplete structure, and to solve it, one must comprehend the relationships between parts of the structure. The gaps are then closed by drawing relevant material from one's previous experiences, which are stored in the brain (KOFFKA, 1935). Gestalt draws on the idea of the Schema, which was conceived by Head initially and developed also by BARTLETT (1961). Many psychologists find it inadequate now, as a model for mental processes, probably because of its Gestalt associations, but in Bartlett's form at least it explains satisfactorily, at pragmatic level, the techniques which are available for tapping one's creative potential.

Bartlett was concerned essentially with memory and the ways in which, over the years, one's ideas develop and change. He took the schemata to be arrangements within the brain of past responses to stimuli and believed that memory changes result from the interactions of the schemata with each other, and with new, external stimuli. The schemata, for Bartlett, were organized according to one's appetites, instincts, interests and ideas. These were concerned with the senses, but also with sport, literature, science, philosophy – any unifying interest into which ideas might be organized. When a new stimulus excited the senses, it was tested against one's existing schemata. The act of perception, therefore, became a two-fold process: first the physical stimulus formed a sensory pattern of the 'real' world, which was then modified by interaction with one's schemata. At the same time, the schemata also were modified by interaction with the sensory stimulus. This led Bartlett to suggest that imagination consists of free constructions on one's schemata, and any technique which encourages creative activity will be based on such free constructions.

In many ways, Bartlett's model is

appropriate also for the central phases of the design process itself – analysis and synthesis. The output from analysis will form the stimulus and may be just as 'real', in physical terms, as the sensory stimulus in the act of perception. But just as in perception, the sensory pattern is modified by interaction with one's schemata, so in conception, the analytical pattern will be modified in similar ways also. GREGORY and BURDIS (1965) have put forward a formal model whose origin may be traced to similar lines of thought (see Appendix to this chapter).

The techniques which are available for increasing one's creative capacity all conform to this perceptual model, whereby an analytical stimulus is forced into interaction with one's schemata. The simplest of them rely on stimulus words to trigger off ideas, and therefore they take the form of check-lists. The Gregory–Burdis model was related to a range of stimuli, including 'challenge'.

Check-lists

The danger with check-lists is that the questions become too vague: 'How can we improve our product?' It should be possible to work out particularly meaningful sets of questions for any particular design-type, but even general check-lists can focus attention with surprising precision onto the difficult aspects of a problem.

OSBORN (1963) and GREGORY (1963) have compiled useful check-lists which suggest new ways of looking at the problem. Osborn's main headings are: 'Put to other use? Adapt? Modify? Magnify? Minify? Substitute? Rearrange? Reverse? Combine?' As an example, under the heading of Rearrange? he suggests the following supplementary questions: 'Interchange components? Other pattern? Other layout? Other sequence? Transpose cause and effect? Change pace? Change schedule?'

Gregory lists his questions under functional headings: 'Economics, Understanding, Practice, Technology, Technological Stretching, Cross-fertilization, Guessing the Trend, New Axes of Reference'. Typical questions are, in the category of Technological Stretching: 'What happens if we push conditions to the limit? Temperature, up or down? Pressure, up or down? Concentration, up or down? Impurities, up or down?'

Classification systems, such as those used in libraries (UDC, Dewey) and the architect's office (SfB) may be useful in this context, but the most accessible list is probably the Tabular Synopsis of Roget's Thesaurus. Roget juxtaposes positive and negative ideas, grouped in pairs, and the most useful stimulus words will be found under the general headings of Abstract Relations, Space and Matter. As an example, Abstract Relations are sub-divided into Existence, Relation, Quantity, Order, Number, Time, Change and Causation. Under each of these headings, there are dozens of words which may suggest appropriate modifications to an object in design. For example, under one sub-heading alone one reads:

CHANGE I. SIMPLE CHANGE

148. **INTERCHANGE – N. inter-, ex-change; com-, per-mutation; reciprocation, transposal, transposition, shuffling; reciprocity, etc.**

Each of these, of course, might be a powerful stimulus word, and the possibilities in Roget range from the simplest and most concrete ideas to the highest flights of abstraction.

Another approach to check-lists is suggested by VON FANGE (1959). He puts forward the idea that a person tends to order the past in terms of a few major experiences which have affected him in each year. These should be listed, and when he is faced with a situation which demands creative thinking, this situation can be compared with the recorded experiences, one by one. For this reason also, it is useful to reread old papers, notes, diaries even, which will stimulate far more ideas than are actually written down. Further useful check-lists will be found in MATOUSEK (1963) and TAYLOR (1961).

Interaction Techniques

Other techniques for stimulating creative associations derive from the use of interaction charts. In the simplest form, one set of factors is plotted vertically, and another set horizontally; associations are then generated by plotting all the possible interactions between these vertical and horizontal sets on a chart.

Attribute Listing

This method, dealt with by Taylor, was devised by CRAWFORD (1954) who abstracts from the object in design a list of its physical attributes. For a screw driver, these might include wooden handle, steel shank, wedge-shaped end for engaging screw, *etc.* These are then plotted vertically and possible variations plotted horizontally, in a systematic manner, against each attribute. In a good field, there will be no obvious vertical links between individual steps in adjacent rows, so that a new solution will be generated by selecting one independent variation on each of the attributes.

Morphological Analysis

This was developed by Dr. Allen Long of Long Beach College and Professor Fritz Zwicky of California Tech; like attribute listing, it is concerned with separating out the independent variables of a problem. Instead of taking the actual physical characteristics, the designer abstracts the relevant design parameters for the object. For the screw driver, these might be: drive element, transmission element, screw engaging element, *etc.* NORRIS (1963) gives good examples.

Forced Relationships

Charles Whiting's method (Osborn; Taylor) is concerned with the relationships of whole objects, rather than with individual attributes or parameters. He quotes the example of an office furniture manufacturer who might be concerned with desks, chairs, desk lamps, filing cabinets and book cases. Whiting would start by considering the relationship between desk and chair, in terms of similarities, differences, analogies, cause and effect. This would lead to a chain of free associations which might suggest a totally new concept in office furniture design.

Group Activity

The most potent techniques for ideas-generation utilize the concept of free association, or 'schema scrambling' in a more Freudian context. The two best known, Brainstorming and Synectics, were both worked out initially in terms of group activity. This has advantages, of course, in that any group can draw on wider ranges of schemata and associations than any individual.

Brainstorming

This is the brash, Madison Avenue technique *in excelsis*. It was devised by Alex Osborn, himself an advertising executive and the intention is that the members of a group shall vie with each other in generating a rapid succession of ideas. Osborn lays down four basic rules for brainstorming:

(1) Criticism is ruled out.
(2) 'Free wheeling' is welcomed.
(3) Quantity is wanted.
(4) Combination and improvement are sought.

It is essential that group relationships be amiable and relaxed; for this reason, Osborn recommends that the session start over a good lunch. The leader states the problem in basic terms, focused on a single point, and throughout the session he is at pains to suppress the criticism of any idea, however crude and irrelevant it may seem. The aim, in fact is to stimulate competition in ideas-generation, by free association, the wilder the better.

Much of the success of brainstorming depends on leadership and difficulties may arise if a group is asked to rework old problems. If these are desperately familiar, von Fange reports that the group will simply restate old attitudes. This is the chief defect of brainstorming, but conversely, a good group may generate so many ideas that evaluation becomes a major task. Osborn insists that all ideas be written down, and that afterthoughts are also added to the list. This is then submitted for scrutiny, preferably by assessors who took no part in the original brainstorming. The most promising ideas are then put forward for verification.

Synectics

In contrast to brainstorming, Synectics on the whole is a quiet, contemplative activity, in which ideas are generated in a purposeful way, and evaluated, as far as possible, during the session itself. Synectics was devised by the Invention Research Group at Harvard University, under the leadership of GORDON (1961). It has some features in common with brainstorming: it is primarily a group activity in which, during a session, personal criticism is ruled out. It can also act as a great stimulus in the individual creative act because, more than any other method, it is designed to draw on the resources of the whole personality. Synectics is a complete design method, including analysis, which is called 'Making the Strange Familiar', and creative synthesis or 'Making the Familiar Strange'; in other words, seeing the familiar problem in a new light. This is achieved by a system of analogy-generation, which is the most striking feature of Synectics. Three types of analogy are identified, (Gordon; GITTER, GORDON and PRINCE, 1965; T. ALEXANDER, 1965): *(a)* personal analogy; *(b)* direct analogy; *(c)* symbolic analogy.

Between them, these analogy-types are capable of tapping the entire range of human experience, which is why they are different in kind from each other – personal, concrete and abstract.

Personal Analogy – The designer identifies himself with the object in design: 'If I were this beam, how should I feel? What are the stresses acting on me? What is my attitude to the supports? *etc.*'

Direct Analogy – The problem is compared with known facts in another branch of art, science or technology. Synectics quotes the example of Brunel who, faced with the problem of building underwater constructions, observed a shipworm forming a tube for itself as it bored into timber. From this, Brunel conceived the idea of the caisson.

Symbolic Analogy – The designer tries to penetrate to the essence of special meaning which he attaches to the problem by means of some personal symbol. This may be verbal, visual or conceivably could take some other form. In one Synectics session, the group was concerned with detecting the presence of an unwamted flame in some complex piece of hardware. They asked the question: 'What is the essence of flameness?' and eventually, thought of it as a 'ghostly wall', which opened up a whole new range of feasible solutions.

Curiously enough, the three key twentieth century ideas of Relativity, Cubism and 12-note Method share a common symbolic analogy in the space–time concept.

In practice, a Synectics session is conducted systematically by a chairman, who introduces the problem, which is then analysed and discussed. At a key stage, there is a 'purge of immediate solutions', after which attention is narrowed onto one particular aspect of the problem. The chairman then asks an 'Evocative Question', which will force answers in terms of one of the analogy-types; once a fruitful analogy has been generated, its implications are examined in detail. Like all creative acts, a Synectics session is cyclic. If no new viewpoint can be established from the chosen analogy, the chairman will guide the discussion back to an earlier phase, and try a different approach.

Synectics draws on the whole creative capacity of the brain. It is concerned with far more than mere ingenuity, because analogy generation, is a very personal thing, depending on the stored associations or schemata which have been built up in the brain over the years. The brain may very well make apparently irrational connections which lead to supremely rational solutions because, however curious they may seem at the time, they have been subjected to the censoring mechanisms by which the schemata control the input of ideas into the brain, their associations and subsequent output. The strength of Synectics, which is shared to some extent by the other methods, lies in the fact that it taps precisely those thought processes which are inaccessible to the computer. At one level, the computer might be programmed to 'brainstorm' itself; it could throw up an enormous range of random associations, but the problem of evaluation would be greater even than with a human brainstorming session. Certainly, it could not be programmed to draw meaningful analogies in the manner of Synectics.

The reasons for this become clear if the implications of 'whole personality' are considered in this context. It is well understood now that creativity is not just a determinist, rational matter, but even if the computer could be programmed to make irrational connections, it could hardly achieve the interaction of body and mind which, increasingly, is being seen as essential to the creative act. One wise and perceptive writer on this subject, Harold Rugg, had almost formulated a theory of creativity in these terms, when he died in 1960. He believed that the creative act involves the whole personality in a two-phased interaction of body and mind. This is known to be true of perceptual acts – seeing, touching, hearing and tasting – which involve physical as well as mental processes. It is also believed that the creative act consists of drawing together associations which have been stored in the mind as a result of these perceptual acts. How then should it be supposed that the conceptual act also does not draw similarly on mental and physical processes?

Einstein seems to bear this out, in a famous statement on his creative processes quoted by Hadamard:

> '.... words.... or language, as they are written or spoken, do not seem to play any role in my mechanism of thought. The physical entities which seem to serve as elements in thought are certain signs and more or less clear images which can be "voluntarily" reproduced and combined..... The above mentioned elements are, in my case, of visual and some of muscular type.'

For this reason, more than any other, it seems clear that, within the design operation a central 'black box' will always be needed which consists of the human brain, working in symbiosis with the human body. There seems to be no other way of building into the design process the mechanism for ensuring that, when needed, a solution will be achieved which is different in kind from the tried and accepted. The remarkable thing is not that this should be so, but that for so long, people have allowed an outworn philosophy of Determinism to lead them into trying to eliminate human 'unreliability' in the design process.

APPENDIX

The crude model of creative behaviour suggested by Gregory and Burdis is shown in *Figure 14.1*.

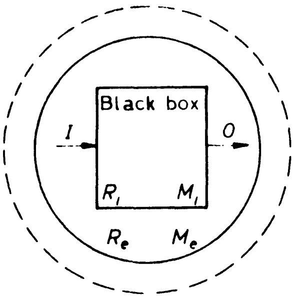


Figure 14.1

The black box is an individual, or a group, or a human–computer hybrid. Input for the occasion is I. This is information of some kind, transmitted in any perceptual system. The resources R_i contain, amongst other things, accumulated information. This is the memory aspect of R_i. Specific operations on I and accumulated inputs are represented by T_s, a systematic procedure which can be programmed. T_c represents a creative procedure.

Considering only a systematic procedure

$$O = f_1 I T_s,\ f_2 (R_i + R_e)(M_i + M_e)$$

Value of operation is

$$V_2 \times f_1 I T_s,\ f_2 (R_i + R_e)(M_i + M_e) - V_1 I$$

If the systematic procedure is unsatisfactory T_s is zero or V_2 is too low. A creative operation is then required

$$f_3 I T_c,\ f_4 [(R_i + R_e)(M_i + M_e) - Z]$$

where Z is a quantity which has to be supplied before any useful result can be obtained. This is some function of the state of the art and also of the microculture and macroculture. The overall value produced, V_{nett}, is

$$V_2 \times f_1 I T_s,\ f_2 (R_i + R_e)(M_i + M_e) +$$

$$V_3 \times f_3 I T_c,\ f_4 [(R_i + R_e)(M_i + M_e) - Z] - V_1 I$$

Under these conditions V_3 is likely to be much greater than V_2.

Some Practical Situations

(1) A highly developed art gives a high value of Z.

(2) New country provides a low value of Z.

(3) A bureaucratic structure, according to the number of decision points, provides a high value of Z.

(4) Cross-fertilization increases $(R_i + R_e)$.

(5) Increased ego-strength provides an increase in $(M_i + M_e)$.

(6) Challenge increases $(M_i + M_e)$.

(7) According to Maslow, as interpreted by Repucci, problem-solving takes 'energy'. If there is a low need-fulfilment, energy is taken away so that problem-solving becomes difficult.

(8) I may come from inside; so also may changes in R_i and M_i.

(9) Z may be circumvented by using special 'unlocking' techniques.

Validation Status

This model with non-linearity included qualitatively summarizes most of the relevant material presented at the Foundation for Research on Human Behaviour: DYNAMAR Seminar, 1965.

Possibilities are seen for quantitative investigation in some aspects.

Chapter 15

CHOOSING AND EVALUATING

A.G. Pleydell-Pearce

Introduction

Design involves choice. Choosing involves acting. Choosing can be capricious, but a person usually believes the choices he makes to be capable of justification. Sometimes he thinks his choices right; sometimes he comes to think them wrong. 'Right' and 'wrong' in this context are customarily held to be 'value terms', of which the right is to be preferred to the wrong. Choosing constitutes a 'critical step' in the human activity called designing. Such a step may in practice be extremely complex. This complexity is apt to obscure the issues involved in the decision-taking situation. Psychological involvement adds its own quota of confusion. I intend, therefore, to look in an abstract way at the concrete problems of designers working in the field. This method of proceeding, since it avoids immediate concern about a particular situation, is less likely to divert attention from the principles elucidated. In addition the increase in simplicity may be paralleled by an increase in comprehension. In any event, if the simple is obscure, the complex can hardly be expected to be clear. Of course, as Nelson Goodman once pointed out, attempting to make the obscure obvious is apt to be unappealing: failure brings confusion, and success banality. But in a field as obscure as that of value theory the attempt at clarification is unlikely to be wholly successful. Some areas of interest will doubtless remain.

I want then in this chapter to do two things: firstly to discuss what is involved in choosing to perform one action rather than another, and secondly to make some general points concerning value theory as such. I shall contend that the evaluation of any particular action is either instrumental or arbitrary. In the latter case the concept 'value' has no real application. Actions are sometimes accorded value because they lead to or are believed to lead to a desired state of affairs. Notice I say 'accorded' value and not 'have' value; although once accorded value, the actions have it in the only intelligible sense. Sometimes they are accorded value because they exemplify a desired state of affairs. The value of the state of affairs itself is not capable of justification. To justify something is either to give a reason for it or to say what caused it. Thus 'justification' is used in two different senses, which I shall refer to as 'justification *(1)*' and 'justification *(2)*'. Justification *(2)* represents one form of explanation, but the two concepts are essentially disjunct; they cannot be reduced one to the other. Justification *(1)* is the primary sense of justification. If an infinite regress is to be avoided some reasons must be reasonless. Cause is a fundamentally confused concept, but for reasons I shall give, the attempt to use a causal account to justify an action taken (at least in one of the central cases of 'cause') is bound to fail.

Some Distinctions

I shall begin by making a number of distinctions: I shall distinguish between actions and sub-actions; acts and projects; causes and reasons; conscious and preconscious choices. On the basis of these distinctions I shall argue that the only problem for those interested in the design of a value system is what, given a projected end, is the most effective action or actions to undertake. This will often resolve itself into a concern with sub-actions whose justifiability, once the action has been clarified, can be given broadly in terms of efficiency. It may be possible to reduce the actions themselves to sub-actions in relation to some more fundamental goal. If it is possible, then these sub-actions can be given instrumental justification like any other sub-action; they will hence be given value in the only non-arbitrary sense. If not, they must be seen as exemplifications of some desired project; they will then not only not be in need of justification, they will also be incapable of it.

I shall mean by *action* any human behaviour based upon and intended to bring about a projected goal or end. Included in this definition are what might be called *negative actions*, which occur when an agent deliberately brings about, or attempts to bring about, a future state of affairs by refraining from action. He takes the conscious and deliberate decision not to act. Negative actions will not be specifically discussed, but for the purposes of the present chapter remarks about actions will be taken to apply *mutatis mutandis* to negative actions also. Care must be taken not to confuse actions with mere movements; concepts such as aims, purposes, ends and projects are needed to distinguish between them. (About movements I shall have nothing to say.) The importance to actions of the listed concepts is furthered by my contention that non-arbitrary evaluation can be introduced only by reference to them. This is one reason why the concept of action should be clarified.

Actions may be overt or covert. Examples of overt actions would be cleaning a car, running for a train, holing in one, *etc;* in general terms, in acting overtly I bring about a change in the external world. Examples of covert actions would be mentally carrying out certain mathematical calculations, composing 'in one's head' a melody, solving mentally a problem in science, *etc;* again in general terms, in acting covertly I do not bring about changes in the external world. Of course, when covert actions are performed changes in the external world, such as physical processes in the brain, do take place. But it would, I think, be misleading to describe an agent as bringing these about, as if he set himself to do this. In thinking out the solution to a puzzle he does not bring about changes in his brain state. Such changes are part of what it is to be thinking at all.

An action may be composed of both overt and covert features; for instance in writing a chapter, one may rehearse mentally a number of arguments before committing anything to paper. An action may also be composed of a number of sub-actions. In many circumstances the same projected end may be brought about in a number of different ways. Agent *A* may obtain a desired fortune by gambling on the stock exchange, by poisoning a rich relative who has noted him favourably in her will, by robbing a bank, by honest labour. . . and some ways will be more effective than others. Some may clash with other projects that he also wishes to bring about; or he may think that they do. Such actions may be simple or complex. *A* may write a letter by taking a pen and making appropriate marks on a sheet of paper, or he may type it; but he may start in one way and finish in another. In each case he will be performing the same action. I shall say however that the sub-actions are different. In the example given neither sub-action is strictly necessary for the completion of the action. He could have used a pencil, or dictated the letter.

A completed action will be termed an *act*. An act may or may not be the one intended by the agent. *B* intends to run a four-minute mile. He runs a mile, but in five minutes. An action is completed, but the act is not the one projected by the agent. Thus to act is not to guarantee success, which is perhaps obvious.

An action may often, perhaps usually, be explicated in terms of a number of sub-actions. How can these two be distinguished? I think in terms of ends. Actions can be characterized by reference to projected or actual ends. To know what action an agent is performing one must know *(i)* what state of affairs he intends to bring about, and *(ii)* what state of affairs he is actually bringing about. When the act is successful *(i)* and *(ii)* coincide. When they do not, it can be said that the agent thought he was doing *x* but that really he was doing *y*. If the projected or actual ends are different the action is different. To change one would be to change the other. Thus if I change my action, or do a different action, I necessarily change its end, which is not the case with sub-actions. I am not, in the appropriate sense, doing something different if I type a letter rather than write it in pen and ink, nor if I start it in one way and finish it in another. There are some cases where *prima facie* this might be so (when, for example, a typed letter is part of the end of the action), but even here there is a choice of appropriate sub-actions. It makes no essential different whether *I* type the letter or whether I dictate the letter for someone else to type. It may be, of course, that an alteration in one or other of the sub-actions will *in fact* lead to an alteration in end, and hence to a different action. Thus in one sense, an observer cannot *know* what a person is doing until he sees what is actually accomplished. If agents were always successful in the projects they set themselves, an observer would know what *A* is doing when he knows what *A* intends. Often he only knows what *A* *was* doing. Choice, however, is concerned with what a person intends, and is characterized by reference to projected ends. Caesar chose to conquer Gaul. Success or failure makes no difference to his choice, though it makes a difference to him. Since this chapter is concerned with choosing I shall consider actions only in terms of their *intended* ends. In this context sub-actions can be thought of as the form or forms that a particular choice takes.

I have distinguished between actions and sub-actions, and have suggested the form that this distinction takes, but this does not mean that the distinction can always be unambiguously applied. in a particular case, the observer, and for that matter the agent,may have difficulty in distinguishing one from the other. This is partly because actions and sub-actions are similarly structured, yet when the agent chooses how to act the distinction may be important. *A* may wonder whether or not the establishment of missile bases near his territory constitutes an act in the sense previously defined. Is it, for example, the end product of a series of sub-actions designed to bring it about (as if agent *B* has said 'Let's do it and see what happens'); or is it a sub-action in a larger purposive plan? *A*'s choice of action will be influenced by the answer he gives to this question.

The Larger Goals

Now it might seem *prima facie* that all acts may be regarded as sub-actions in relation to the larger goals that a person may set himself. But this hypothesis is, I think, a mistake; not because it assumes that people entertain long-term ends of the requisite kind, nor *just* because it assumes this (though if people did not entertain these ends it would be). I shall indicate later the kind of mistake it is. Here it need be said that the agent does, in practice, make the distinction outlined above, though it should be added that, if pressed, he will make it at a number of different stages. There is a clear sense in which I can, and perhaps will, say once this chapter has been written 'Well, that's done!'; just as there is a clear sense in which it would have been inappropriate to have uttered the phrase as I successfully picked up my pen to commence writing. But would it be equally inappropriate to think of the writing of the chapter as a sub-action intended to bring about some further end – participation in a symposium, for example – and to think of this in its turn as instrumental in fulfilling further aims and purposes? Here the kind of mistake involved begins to become clear. The ogre of infinite regress appears. Not every action can be done for the sake of some further action. Acts, like Tennyson's time, must have a stop. ARISTOTLE noted this at the beginning of the *Ethics*, but I shall not go on to draw the conclusions that he drew. I shall indicate later that acts may come to a stop in two different ways, though perhaps only one of these is typical.

The infinite regress argument is troublesome in another way. The only effective way to avoid it is to argue that sub-actions are always capable of justification, but that actions never are. Human acts may then be accorded justification to the extent that they can be reduced to, or legitimately characterized as, sub-actions. Those which cannot be so treated must remain unjustified, and indeed incapable of justification. Ultimately their performance is arbitrary, and it is because there is a resistance to the arbitrary that the argument is troublesome. One expression of this resistance can be seen in the promulgation of the traditional so-called objective theories of value.

A prejudice against the arbitrary is not the only difficulty encountered in this field. Another is that many projected aims and purposes are often essentially obscure. Sometimes the obscurity can be removed but sometimes it persists. Its persistence does not, of course, prevent a person choosing; nor does it prevent him acting, since choosing entails acting. To choose *x* is to attempt to bring it about, and in this respect choosing must be distinguished from mere wishing. A person may wish for *x*, but if he does nothing to bring this about he can scarcely be said to have chosen it. The prisoner may wish to be free, but he can only be said to have chosen to be free if he takes some steps to achieve it. *x* may be chosen derivatively, in that *y* may be chosen in order to bring about *x*. This is the normal relation of sub-action to action: the justification for choosing *y* will be given in terms of *x*. But if one is to choose at all one must act. (Here *choosing* to do nothing can be characterized as acting negatively, as distinct from not choosing and doing nothing.)

The action performed must be characterized in terms of its end, but this does not mean that the agent must be able to give a precise description of either the end or of what he is doing. If a child tells an observer that he is counting the number of bricks in a box, the observer knows what he is doing, and so does the child. It is not merely that the observer can name what the child is doing; he can do it himself. However if asked what I am now doing I may reply 'Writing a chapter', but having said what my action is I have still given no precise description of it. Further questioning as to the kind of chapter and what it is about may help to fill the gaps, but a precise description may be impossible. Of course I have *some* idea of what I am doing, since only then can I construct the steps which I believe to lead to the purposed goal, but at some points along the way the goal is the merest outline, a schema the details of which I may not know myself until the action is completed. Thus actions and sub-actions may, even for the actor, have only relative clarity: they can be seen as lying along a continuum from those cases where the projected actions and sub-actions are the merest sketch to those where both can be clearly delineated. An example of the former is painting a picture. Here the goal may be only the vaguest schema. The artist cannot in advance say what precisely his end is, nor can he formulate the precise sub-actions necessary to bring it about, but his behaviour with brushes and paint is not entirely random.. It is directed towards a goal, however loosely schematized it may be. At a certain stage the painter may put down his brushes with the awareness of having completed a task not previously describable in detail. '*That's* what I was after' he might say to himself. Here his behaviour may be likened to a voyage of discovery into relatively unknown territory. By the very nature of the venture the voyager cannot, in advance, say what kind of territory he will find or what precise features it will possess; nor can he say just what the character of his behaviour will be. At the other extreme the actions and sub-actions may be clearly defined. An example of this might be making a pot of coffee, where past performances help to lay bare their relevant details. Between these extremes are any number of possible actions and sub-actions capable of various degrees of prior clarification, as are the relations between them. It is one thing to set oneself to win the love of a desired woman. It is quite another to know precisely what to do.

Actions then may be described with varying degrees of clarity. Sometimes the obscurity is of the kind mentioned above, but sometimes it is rather different. It is arguable that some choices are preconscious. Note that I do not say subconscious, since there seems to me an important difference between the two. The part of this difference which concerns the present chapter will subsequently be made clear. By preconscious choices I mean choices capable of discovery by certain techniques of introspection, though I do not suppose that these techniques are always or even usually available to all persons. I do not think that preconscious choices can be *causally* connected with conscious ones, and this is the important distinction between them and subconscious choices, at least as 'subconscious' is normally used. The use of the concept *preconscious choice* is to give *meaning* to many of the actions we perform. This is often overlooked owing to the inherent ambiguity of the question 'Why did you do x?'. This ambiguity shows itself in the different uses to which the term 'motive' is conventionally put. When asking for a person's motive in doing what he did one may be asking 'What are your reasons for doing what you did?' or equally 'What caused you to do what you did?'. And by *reasons* one may mean the reasons that a person is able or prepared to give; but one may also mean the reasons he had for doing what he did, whether he was able and prepared to give them or not. The concept of rationalization has a role to play here, for instance when one wonders what *A*'s *real* reason was. People are thought to deceive themselves about their motives for action, though 'deceived' in this context needs more careful unwrapping than it customarily receives. However, I want to concentrate upon the difference between *reasons* and *causes*. This difference was characterized by SCHUETZ (1951) as the difference between 'in-order-to' and 'because' motives.

Causal Accounts and Determining Factors

This is not the place for an extended analysis of the concept of *cause*, but some points need to be made if only because they are usually ignored. Take for example decision-taking and creativity – two classes of human behaviour clearly relevant to the design process. On occasion one wants to influence decisions, or to increase creativity. One can ask in a specific case for the reasons that support a particular decision against another, and one can gain some influence in respect of the decision to be taken by producing reasons thought to be relevant. It is plausible to suppose that decisions may be influenced by less rational means: for this reason Public Relations and Advertising find employment for psychologists. It is not so clear that creativity can be increased by the presentation of reasons intended to show the need for such an increase. Here an understanding of the nature of the creative activity would clearly be of use. If its cause could be explained, current techniques for increasing its incidence might well be vastly improved; but just what kind of explanation would this be? Once again the very complexity of the examples tends to obscure the points at issue. Concern with explaining particular instances of human behaviour may lead one to ignore prior assumptions, although these have their own importance, at least for those interested in the theoretical status of 'explanation' in the human sciences. What, after all, does a causal explanation imply?

The supposition behind the traditional causal account of human behaviour is that people act as they do and choose what they choose, because of certain determining factors, which are briefly describable in terms of heredity and environment. Such descriptions take the form of reference to physical, psychological, social, and historical conditions. It cannot, I think, be denied that these do constitute determining factors. To what extent an agent's beliefs are so determined, and to what extent his beliefs determine his choice to act in one way rather than another, is a matter for detailed debate. It is sometimes said that *A* believes what he wants to believe. This, if correct, would mean that in some cases at any rate it is not the beliefs that determine what *A* chooses, so much as what *A* chooses determining what he believes. But that beliefs have some influence upon behaviour seems scarcely deniable. For *A* to act at all he must see some different state of affairs as possible. If he has been led to believe, and does believe, in the impossibility of *x* he is unlikely to attempt x. The nature of the influence of beliefs upon choice however depends upon whether it is a choice of actions or sub-actions. If *A* believes that punishment may follow a course of action there are two ways in which this belief is relevant to what he chooses to do. It may affect the sub-actions that he performs in carrying out his project; they may, for example, be designed to escape detection. It will not necessarily make him abandon his project, though it may do this. How inevitable he believes the punishment to be will be a relevant factor, but it will not be wholly decisive. Suppose *A* does believe that punishment cannot be avoided (*e.g.* punishment by an all-seeing, omnipotent god). Will this of necessity cause him to abandon his project? It seems not, since he may choose the project despite the disvalue of the punishment. A decision to pursue the project would be evidence for this. But *A* may choose to be a thief in a society where he believes punishment to be avoidable, and honest in a society where he believes it to be inevitable. If he is taught and believes punishment to be unavoidable the choice of actions open to him is not obviously limited. This circumstance will not force him to evaluate punishment in one way or another, but if he chooses it as something to be avoided at all costs then his choice of actual actions will be limited by his beliefs concerning its inevitability. Some restriction will have been imposed.

Beliefs, of course, are not held to be the only determining factors. Emotional pressures are also high on the list of effective causal agencies. These in their turn are often given a causal explanation in terms of human physiology (*e.g.* the chemistry of the human organism). Here, too, a more detailed analysis is required before the relevant issues can be properly clarified, but for present purposes such an analysis need not be provided. Few, I think, would deny that the choices people make are conditioned in certain ways: the argument is more likely to be over the extent of the conditioning. But some would argue that the causal account in its proper formulation presupposes the possibility of an account in completely deterministic terms. Explanations fail out of ignorance, not because the causal account cannot in principle be given. Against this others would assert an in principle impossibility in the demand for such an account. This takes the form of demonstrating that the account fails through circularity. The argument can be put in a number of ways. For convenience I shall sketch the account given by HUSSERL (1965) which I shall call the 'natural science account'. Husserl argued in effect that in assessing the value of this account one should not forget that doing natural science is a conscious human activity.

Indeed the term 'natural science' names such activities on the part of natural scientists (psychologists, sociologists, biologists, *etc.*) working in co-operation with one another. These activities are amongst the things that the natural scientists are called upon to explain. Is it not then circular to use natural science to explain the 'event' natural science itself? Psychological and other laws of nature are called upon to explain their own production. Produced by the contributions of scientists they are themselves part of the problem.

A similar but different argument can be put as follows. Supposing that it were true that everything people do is causally determined, then everything they say would be so determined. Amongst the things so determined are the utterances of scientists. Amongst the things uttered are particular causal accounts of what people do. Thus the reasons such scientists give for any account cannot be the real 'reasons'. The real 'reasons' are the causal agencies in virtue of which they *cannot help* saying what they do say. So why then should any *specific* account be taken seriously?

The force of the circularity account depends upon taking the causal hypothesis to be fundamentally descriptive. If it is taken as primarily methodological the circularity, whilst it does not disappear, becomes irrelevant to the scientific enterprise. But then one should be wary of the tendency of this enterprise to encourage one to prejudge the issue. The point is not merely academic. The causal hypothesis lies behind most thinking in the fields of science, technology, and design. Yet its precise status remains obscure, as do the relations between the disciplines it appears to support. The latter obscurity is aggravated by its own ambiguities. 'Science' appears to name a unitary activity, but how unitary is it? DUHEM (1914) for example, thought that the empirical hypotheses of a science like physiology were radically different from the theories of physics. The former were descriptive; the latter had largely symbolic content. Any attempt to assimilate physical theories to physiological hypotheses was an error. This is not the place to repeat the arguments relative to this position, nor am I here much concerned with its validity. I *am* concerned to point out that seeing how science relates to design entails holding views about the nature of the scientific enterprise. It is these views that dictate the character of much talk in this field. Given that Duhem's claim may be made plausible, as I think it can, a number of *prima facie* possibilities present themselves: a particular science may be wholly descriptive; it may be wholly non-descriptive; or it may be poised between the two. If the latter, it may be predominantly descriptive, or it may be predominantly symbolic. It may be neither. I do not take the issue to be closed, but I do take the elucidation of the relation of science to design to involve taking up a position in this debate. In practice this may engage attention only when things go awry, but I would not on this account regard the issue as of any less importance. That science and design are in fact related seems hardly in doubt, although the nature of the relation is. Ergonomics presents a case in point, since it applies physical, physiological, and psychological findings. But what is the nature of this application? How like physics is physiology? How like either of them is psychology? Opinions differ, and the issue of descriptive versus symbolic has still to be settled. There are divergences of opinion as to whether or not the laws of psychology are nomothetic (like those of physics) or ideographic. If we are theoretically concerned with the role of ergonomics in design, the account that we give of it will be influenced by a prior account, as will the one that we will accept. This prior account will depend upon issues of the kind raised here, although what would make this prior account a correct one is not *prima facie* clear. Even if it were, the causal issue would still be in dispute.

Justification

In these circumstances it remains very much an open question whether any account of 'choice' in terms of *because motives* can do the job that it is intended to do. Even if the causal account could be made to work it would not do so in the required way. It would provide a justification in the sense of providing an explanation – what I have called justification *(2)* – it would not provide one in the sense of justification *(1)*. To explain causally *A*'s embezzlement of his company's funds would provide justification *(2)* for his action but it would not provide justification *(1)*. In assessing in this sense his action, the *reasons* he gave for acting as he did would be relevant to this assessment. They would not be relevant, or at any rate not relevant in the same way, to assessing the validity of the explanatory account. As Freud noted in respect of religious beliefs, to explain *why* people hold the beliefs they do is to say nothing about the truth or falsity of the beliefs themselves; though given the one it may be difficult to take the other seriously. But if the beliefs are false they will not be shown to be so by explaining how they came to be held. Analogously, to explain *why* *A* chose *x* is to say nothing about whether or not he was justified *(1)* in so choosing. But what sort of justification is justification *(1)*? In my view only instrumental.

Now it would be wrong to think that it is always possible to use instrumental justification. Not all acts (*i.e.* completed actions) can be seen as contributing towards the realization of a project. Some can, but others merely exemplify these projects. Thus *A* may punish *B* because of the ends to which this action leads or is thought to lead. This is the form of the deterrence theory of punishment. *B* is punished in order to prevent others from doing as he has done, as well as to prevent *B* from repeating the offence. What the agent wants is a society which will be free of the kind of act that *B* has performed. Alternatively *A* may punish *B* because such an action exemplifies some aspect of the kind of society that he wishes to promote. This is the form of the retribution theory of punishment, which is simply the view that it is 'right' to punish what is believed to be wrongdoing. It is not (as is sometimes mistakenly supposed) an argument *for* punishment. The two views are not of necessity incompatible, although they *are* very different. The first claims the action to have instrumental value; the second that its value comes from its exemplification of an accepted institution for which no argument needs to be provided. In each case the goals involved may be either conscious or preconscious, and in each case acceptance of the goals is necessary before any value can be predicated of the actions performed. Without human aims and purposes the term 'value' would be devoid of meaning.

In terms of justification *(1)* only sub-actions can be defended. Such a defence can always be attempted in terms of efficiency, expediency, availability, *etc.*, in respect of the completion of projects. The difficulties in practice are well known. The variables in any choice situation are likely to be near astronomical. The agent is likely to be ignorant of many of them. The projects of others, which the agent may or may not be aware of, will ideally need account taken of them. Projects can only sometimes be clearly characterized, but often they cannot. Yet the ability to choose appropriate sub-actions is not independent of this clarity. Also, given the choice of sub-actions the agent would ideally wish to deliberate concerning their respective merits. This would entail making accurate probability estimates concerning the chances of a sub-action successfully furthering the project in hand. It would also entail an awareness of the relation of the sub-action to other things that the agent requires: *i.e.* seeing how his various aims and purposes are related to one another. If the *only* way *A* can obtain *x* is by theft he may decide to go without *x*. Instrumentally such deliberation would appear always to have value. Yet the apparently less valuable may sometimes be preferred. In an emergency situation a decision which is random but quick may be preferred to no decision at all. The considerations of detailed application are legion. However, none of this affects the general point that reasons can be given for sub-actions, but that they can be given for actions only within a framework where these can be reduced to sub-actions. Where this is not possible their acceptance by an agent is arbitrary.

It may be thought that the above account is guilty of a form of the 'naturalistic fallacy'. If it were I would not regard this as fatal, since I do not believe the 'naturalistic fallacy' to be fallacious in the required sense. The arguments for it work only if there is already dissatisfaction with the conclusion that value terms can be identified with those expressing natural properties. If it be argued that the phrase 'x has value' doesn't *mean* 'x will further *y*' this is, of course, so. 'If *x* has value then *x* furthers *y*' is not analytically true. It is not self-contradictory to assert that *x* has value and to deny that it furthers *y*. Nor is it analytically true that if *x* furthers *y* then *x* has value. It would not be self-contradictory to assert that *x* furthers *y* and deny that *x* has value. I argue, however, that if *A* chooses the ultimate project *y* then if *x* furthers *y*, *x* has value; since if the above account is accepted it *would* be self-contradictory to assert that *A* chooses *y* and *x* furthers *y* and deny that *x* has value. [Though we should note that this would not in itself justify *(1)* *A* doing x.]

The contention that this would not be self-contradictory presupposes the above account to be false. It does nothing to *show* that it is. Thus if *A* chooses *y* and *x* furthers *y*, *x* clearly has some value. Has it, that is, in the only intelligible sense in which value can be possessed: instrumentally. The mistake would be in thinking that to say *x* has value means only that *x* furthers *y*; or that only what furthers *y* has value. This is clearly not so. *x* has value when anyone chooses *y*, and when anyone chooses any other project that *x* furthers; but it makes no sense to talk of the value of the ultimate project (in this case *y*) itself. Here the concept *value* has no application. That this is not always apparent is due to the large measure of conformity over accepted projects in a specific society. Considering the efforts normally expended to ensure conformity, this is not, I think, surprising.

Chapter 16

DESIGN AND DECISION

S. A. Gregory

Introduction

This chapter is concerned with knowledge of the design method and the benefits which may come from its practice. One possible advantage lies in the fact that method can be taught. More important is the strong belief that by a methodical or systematic approach, the chances of producing better designs may be improved.

Design may be seen as a perpetual struggle between fertility of ideas and choice, with choice in the form of decision having the last say. It may be characterized as a sequential decision process. Therefore, concern with method in design must also entail concern with method in decision. But in addition, because many decisions have considerable consequences it is important that they should be laid bare ('externalized') so that people inside an organization or system know the grounds on which decision is reached. The knowledge of decision-bases is the full knowledge of constraints. Some students of decision are prepared to see it 'as a means of making an organizational response to a situation' (GORE and SILANDER, 1959).

It is not intended to imply that by a systematic method it is possible to arrive at all decisions; far from it. What needs to be recognized is the limit to which system may be pushed and the place where rational approval must be accorded to non-rational procedures. Further, there must be recognition of the differences between decisions possible in closed and open systems.

The conscious study of decisions grew up in management studies about half a century ago. The last fifteen years have seen a considerable expansion of interest in the topic, stimulated in part by the successes of operational research (BROSS, 1953), and in part encouraged by the hope that, within economics and some of the behavioural sciences, it might become possible to extend greatly the sway of rationality. Some of the decision procedures may, in fact, be traced back at least two centuries to the discussions of Bernoulli on the effects of probability and utility to the gambler.

Designers have always made decisions, but, in most cases, they were certain to have been 'internalized'. If design decisions are to be brought out into the open and be made systematic designers cannot blindly take over decision theory as developed at large and expect that it will necessarily fit design. What is needed is more information about the actual practice of decision in design coupled with suggestions about the way in which the corpus of existing decision theory may be used.

Decision may be seen as a substantial point of difference between the design method and the scientific method.

Decision in Design

In accordance with what is now generally accepted as the design process it is possible to see each stage in the route from perception of need to the commissioning of the product as terminated by a decision, whether formal or informal. Within each of these major decisions may be many nested decisions. Relevant to this is HALL'S diagram (1962) in which he proposes partitions of the field of decision-making

(Figure 16.1). Within the general approach of this diagram, an 'ends' decision requires the detailed establishment of objectives which will usually include statements about: profit, market, cost, quality, performance, competition, compatibility, adaptability, longevity, simplicity, safety, legal and/or ethical constraints, and intangibles.

In sequence from perception of need onward the decisions may be expected to vary in character. These variations may be due to the technical content of the design, to the novelty of the subject matter, to the prevailing circumstances of the environment, to the personality of the designer responsible, or to the way in which the designer himself is controlled. These variations in approach turn, in the last analysis, upon some function of information and its appraisal by individuals.

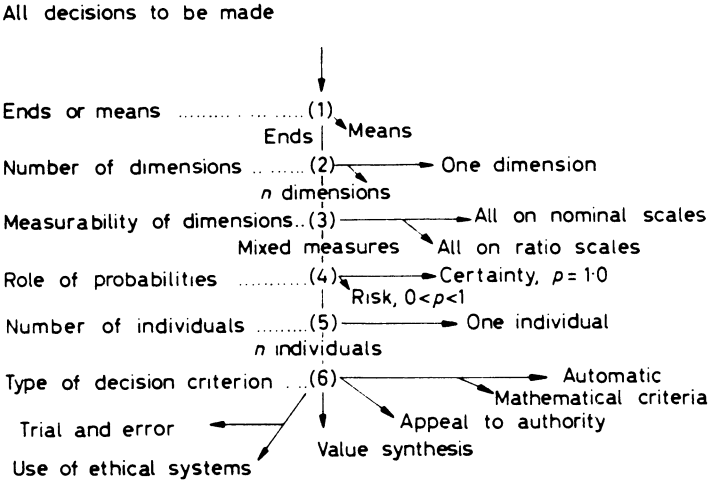


Figure 16.1. Partition of decision-making (after Hall, 1962)

Decision is a choice among alternatives made by the person responsible for the outcomes. It is important to distinguish this from any prior activity such as evaluation or the calculation of probable effects. The decision is not made by the calculation or the test run but by the individual responsible.

In its simplest form design is seen as finding the quantity or the dimension, the shape or the material, to fit a carefully specified requirement. Much of the teaching of design falls into this area, including at the same time considerable emphasis upon certain restricted methods of modelling and communication. In this, decision turns upon determining whether there is a match between the design and the requirements or that some limit is not exceeded. Whenever a model is used a decision has to be reached about its content of uncertainty.

This kind of design is characteristic of a non-dynamic market within which engineering operates upon a range of well-known products using materials whose properties are established adequately. This kind of design is not adequate for present-day circumstances and the last half century has brought an increasing interest in optimization procedures for well-developed items, and techniques of prototype and model testing for items undergoing development. Optimization procedures themselves may be said to have reached a high state of development, even if they are not applied as much as they might be because of the lack of awareness of the power of these economic tools and because of the difficulty of putting some of them into effect. In spite of this, the optimization process is the principal aid to decision in the design of highly-developed products; with new products the test procedure is probably the principal arbiter. The rise of the computer has intensified interest in linear programming for optimization, in abstract models for testing designs, and in the search for models adequate for treatment by perturbation to provide information on optimization.

Studies of Design Decisions

It is important to look at practical cases of design in order to be certain that designers, or other people, make design choices; that the different kinds of decision may be found, and that the possibility may be studied of linking practical decisions with what theory may suggest.

In spite of the very great number of designs which have been made there are very few readily available published studies which throw light of consequence on the practice of decision in design as it took place in fact. Two principal studies of this type are those of MARPLES (1960) and GREGORY (1964). In his paper Marples reports on two designs which he observed as a non-participating engineer. The designs are largely concerned with mechanical embodiment. The paper of Gregory is broader in scope and deals with marketing, process design, mechanical embodiment, and production; he writes as a participant.

Marples sets out his findings in the two cases in the form of a tree diagram. This diagram begins with the greatest level of abstraction and becomes successively more branched and carrying more detail. In his words: 'At the bottom we envisage detailed bits of hardware made from particular materials.' At each level a number of alternative proposals would be generated and investigated. Marples sees design proceeding in stages, 'the end of one and the beginning of another being marked— usually quite dramatically at a recognizable instant – by a decision which chooses a particular solution from among a number and sets out the sub-problem to be tackled in the next stage ... A number of features characterize the "critical" decision. First, it is taken by someone much higher in the executive hierarchy than the designer who explores the consequences of proposed solutions...Second, the decision is treated as if it were irrevocable...Thirdly, the activities of the team undergo a marked change.'

Marples states that decisions are made by comparing the various proposals against a set of criteria, but that these criteria are not obvious. 'The list cannot be laid down at the outset, because, until the proposals have been examined it is not possible to say in what respect they differ.' It is possible to draw up lists of criteria in the abstract (these would constitute check-lists) (see MATOUSEK, 1963). Marples refers to 'general engineering values' which are independent of a particular design, and to engineering values which belong to the design. Any decisions made must take cognizance of natural properties, engineering values and prior decisions. Prior decisions include time, manpower and expense budgets. Each decision takes account of these and of predictions regarding the outcomes of sub-problems. Tests, calculations, models and drawings are made to help predict the future behaviour with greater certainty and to reveal sub-problems.

In summarizing his paper Marples states that it is likely that his model applies only to problems requiring novel solutions and not to those where the form of solution is known but conflict over the choice of parameters exists.

In extending this point made by Marples it is important to note that he reported on organizations engaged in designing equipment for their own use. The requirement was certain and there was no great competitive sanction on product price. The principal uncertainty admitted was in connection with the outcome of sub-problems. The strategy to deal with this was to choose a solution giving the greatest ground for manoeuvre.

Marples is supported in part by a paper from BOOKER (1962) which, although not immediately concerned with the study of decisions, throws light on the decisions reached in his study. He reports on a design problem which he was able to follow as an outside observer, giving at the same time the design setting and the comparable work done in other organizations. He reports on the generation of possible designs for a given purpose by the intensive utilization of precedent from any relevant field already existing (*i.e.* morphologically similar solutions). In the course of discussion he refers to decisions made upon general engineering values and to engineering values specific to a design, although not employing this terminology. Booker writes against a background which is aware of competition in the form of alternative sources of supply of hardware, although, in the particular case, much of the uncertainty of the market was missing. Against this background he is much more conscious of the need for conservatism in design, a conservatism which is satisfied by the use of precedent (leading to more certainty in design decision and, later, by the same feature, affecting customer decision – a precedent eases innovation). There is subsequent appeal to model tests of all kinds, from mathematical, through analogue, to more obvious forms.

Gregory's paper is concerned with the design of an innovative plant system under competitive conditions. He connects the design with market requirements and carries it through to the conditions of service after sale. He is concerned with feasible methods and also with optimization procedures. At the end of the paper he analyses the major decisions taken and the considerable extent of uncertainty involved, even in what appears to be straightforward optimization. Attention is drawn to the need for absorbing or dispelling uncertainty. He records particularly the deviation of the observed decision processes from what might be suggested by the engineering literature.

Modern Decision Theory in Relation to Design

The last five years have produced two clear currents in thinking about decisions. The rise of interest in system design has led to analysis of the problems of feasibility, optimization, and values. This has drawn upon the accumulated studies already made in other disciplines (*e.g.* HALL, 1962). At the same time workers concerned with disciplines having relationship with the behavioural sciences, have tended to review decision theory in the light of their own problems of decision (GORE and DYSON, 1964; COOPER, LEAVITT and SHELLY, 1964; SHELLY and BRYAN, 1964). Much of this kind of thinking has tended to show the essential limitations of what has been termed 'closed' decision processes.

Feasibility determination is a *desideratum* for all decisions in design. Where the design is highly developed there is usually little formal questioning of feasibility and the stress is on optimization. On the other hand, with innovative design, or completely new design, feasibility is of prior importance. In many cases, particularly with new design, optimization is almost impossible. The important thing is that the design should work. It is not always possible to test out a full-scale design, as in the case of a bridge, so that model testing may assume importance. In some fields the model tests are extremely complex and may lead to the pilot-plant. But in view of the costs involved every effort is normally taken to undertake only that amount of work which will provide sufficient knowledge for the reduction of uncertainty to the point where a decision may be made. Page's strategy involves this, together with the deferment of decision until all reasonable alternatives are examined.

The introduction of thought about values, which is particularly associated with system design (Hall), arises from the substantial social consequences of major system development (LICHFIELD, 1964) and with the extent of man–machine interaction within the system. Most of the thought is concerned with a search for possible guidance from prior thinking about values, particularly by philosophers. The entry of values into decision-making in design is not by any means a conscious matter and the extent of unconscious influence of values over design, both directly and indirectly, on the part of the designer and of the environment, is worthy of more study and has been touched upon elsewhere in this book. Such unconscious influences may well suggest that a system is closed when, in fact, it is open, and decisions have to be arbitrary.

The application of formal decision procedure recommended for design largely turns upon the use of statistical decision (STARR, 1963). In this a payout matrix is constructed in which values are put relating possible designs or alternatives to probable states of nature. After the application of any suitable simplifying procedure the best strategy is read off.

This kind of procedure is employed as a guide to decision-making under risk (DMUR). A risk situation is one in which there is sufficient information about past behaviour to provide statistical indication of the occurrence of particular states of nature. There is information which may be termed objective probability.

Two other kinds of decision-making are distinguished: decision-making under certainty (DMUC), and decision-making under uncertainty (DMUU). Authorities vary about the relationship between the three kinds of decision-making. The simplest suggestion is that DMUC is an extreme form of DMUR, in which the probability of a state of nature approaches unity. At another extreme is DMUU in which there is no information about the probability. To use the payout matrix certain assumptions have to be made.

Subjective Probability

Where statistical data exist or probabilities may be calculated, it is possible to apply them to analyses of design provided that the proposed product is to be manufactured in reasonable population quantities. Where a single item is concerned the estimation is less obvious. The states of nature occur over a range of values. One method of dealing with this kind of situation is to consider the range of values and make allowance for the possibility variety of outcomes. This is a sensitivity analysis.

What is the situation with subjective probabilities? By this is meant an individual's estimate of likelihood in the absence of objective data. How valuable is this information? What can be done with it? There is a great deal of current interest in this problem.

It has been suggested that subjective probabilities may be substituted for objective probabilities in payout matrix calculations; that a group of people may be asked to make subjective estimates which are then averaged in some way or which are used to provide the range of variation for a sensitivity analysis.

This kind of approach has obvious weaknesses. Clearly some people are better at making subjective estimates than others; indeed they may be using cues which amount to something more than an absence of objective data. In some cases creative people have the ability to offer estimates which form the basis of self-challenge to fulfil a task (GREGORY, 1963, 1965). How does the decision-maker grasp another's subjective estimate? How does the decision-maker choose the people for his assessment panel? How does he weight their values? It is best in such a situation to be able to rely on an individual's demonstrated ability and to make sure of his involvement.

Certainty and Paying for Information

It is a general rule of organizations to attempt to eliminate uncertainty from their transactions in some way. The ideal situation is that in which decisions are made under certainty, and it is this situation which managers attempt to create, particularly within the bounds of their own specialist responsibilities, by pushing uncertainty outside the borders. It is this situation which many technologists see as the natural state of affairs (*Figure 16.2*).

What constitutes certainty is largely a matter of practice and attitude. What is reasonable certainty in one design office is not reasonable in another design office. Of this I am very conscious as a result of practical experience. I believe that the difference in attitude may be attributed in part to the organization as a whole (a top management responsibility) and in part to key individuals in the design field.

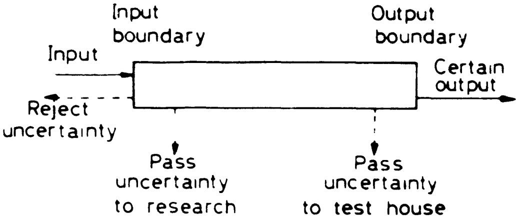


Figure 16.2. Elimination of uncertainty

From an analysis of design behaviour, not previously reported but noted in connection with the studies of decision cited earlier (GREGORY, 1964*a*), I venture to suggest that it is possible to classify the relative status of information in terms of its content of uncertainty relative to a given organization as follows.

Certainty Status of Information

(1) Successful office precedent design reported in detail.

(2) Licensor successful precedent design reported in detail.

(3) Own laboratory information from prototype.

(4) Own laboratory information from pilot plant.

(5) Well-established textbook information.

(6) Precedent outsider full-scale design reported in literature.

(7) Precedent outsider full-scale design from private reports.

(8) Outside laboratory information from prototype.

(9) Deduction from first principles.

(10) Estimate of possibility by expert.

The status will vary from company to company and will dependupon the state of the art. It will also depend upon the stage in the design process and upon the magnitude of the operation as a whole.

The datum is office practice in the company. This will differ from department to department, depending very much upon group experience and leadership and the class of work done. Given the datum then any design which departs from this requires to be operated upon in order to make it acceptable. The greater the departure from the datum the more the work required to be done. The work might consist of intensive technical discussion accompanied by nagging and banter; it might involve sending someone to visit a distant works; it might mean permitting a conservative dissenter to spend a substantial period of time exploring some alternative suggestions; or it might mean laboratory or works tests. Practice showed that unless something of this kind was executed tension would develop leading to results such as 'working to rule', going sick, having a direct argument, or causing a superior to summon an investigation. Under certain circumstances the situation might be such that a proposal would not be accepted, leading thereby to a loss of opportunity. What was most remarkable was the observed need to repeat work already presented in report form from another organization where the work has been carried through under the supervision of the person proffering the suggestion. His information was treated, in fact, as if it had been subjective.

Within such a perspective it is easy to see that test procedures themselves can have different degrees of uncertainty. The same holds true for the less expensive and less information-rich model situations. Working models are less expensive to set up and test than prototypes and they may be limited in information. Calculations take less time and money than working models. Each of these procedures involves some kind of model but may only be used for the basis of decision provided that the level of scrutiny and the quantity of information associated with it are adequate for the purpose, *i.e.* to reduce the uncertainty of the situation.

These observations suggest that it might be possible to characterize the attitude of design offices by their reactions to different types of information material. Examples might consist of reports of experimental work carried out in their own laboratories (note possible differences of value between researchers); reports of other people's experimental work published in the literature; word-of-mouth reports given by a competitor's employee; reports paid for either from a consultant or from a licensing firm. Another series of reactions might be sought dealing with the amount of reliance placed upon tests on a wide range of models, from prototypes to the most abstract, complete with simplifying assumptions.

Where Certainty is Impossible

Certainty, *i.e.* substantial certainty, is not possible in a very large number of practical cases. When market demand is high and offtake is relatively certain then difficulties are likely to arise with raw materials and production methods. (Such a situation exists in the Midlands at this moment.) When demand is low competition will be particularly active (*Figure 16.3*). These market situations hold even when the product itself is technically well established.

Estimating the market's pattern for some years into the future has many difficulties. In spite of good trend data, any one year may be much out of line. Where relevant the complication of fashion and subjective values need further consideration. Even with technical matters there are other problems; for example, it is difficult to determine adequately whether a given technique or production will persist.

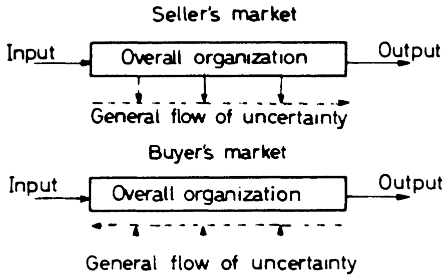


Figure 16.3. Uncertainty flow and dependence on market conditions

For reasons such as this economists have developed methods of discounting the future. The discounting effect must be greater in fields where development or change are likely to be rapid, as opposed to the situation in a stable state.

Certainty is impossible in the production of a radically new design, particularly where many alternatives offer themselves. It is not possible technically to explore all the alternatives in depth. Some strategy must be introduced to cut down the number of alternatives considered. The introduction of this strategy has to be done in such a way as to carry conviction in any decision.

Every creative design which deserves the name introduces problems of decision. Every fresh attempt to produce a creative design in an existing field means the questioning of rational decision.

Decision and the Individual

Some remarks have been made earlier on subjective probabilities and the effect of experience, unconscious cues and involvement. It has also been suggested that practice shows a difference between individual and individual and also between organizations in respect of the amount of uncertainty which may be accepted in the making of a decision.

This difference between individuals may be discussed in terms of utilities and also in terms of general personality make-up. Utility is concerned with the value of outcomes to an individual and is greatly influenced by that individual's existing state. Thus the gain or loss of £10,000 is likely to have much greater significance to the normal designer than to a millionaire. It is possible, with some careful work, to establish utility curves for individuals. This has been done by GRAYSON (1960) in studies of oil-drilling decisions. It is possible, provided one has such values, to use them in a sensitivity analysis.

In addition to the individual's employment of a given level of uncertainty as a jumping-off point for his decision, and his appreciation of the consequences to him in terms of reward or punishment (JAQUES, 1956), it is possible to adopt different decision rules which, in their turn, may be related to the characteristics of the individual, although formally they may be the expressed policy of an organization.

The range of these rules is now well described in the literature (*e.g.* Starr). The earliest is the Bayes–Laplace criterion. This states that, since one has no information about the states of nature and the situation is quite uncertain, it is reasonable to assume that each state of nature has the same probability. In this Nature is taken as neutral in its dealings with the individual.

The *minimax* criterion of Wald assumes that Nature acts as an enemy. Under these circumstances the rule is to choose that outcome which provides the minimum loss. The *maximin* criterion is also pessimistic but rather more positive: it relies upon the choice of the outcome which gives the largest minimum payoff.

To accommodate the optimist, the man who believes that Nature is on his side, the rule is to select that course of action which provides the maximum of the maxima. The Hurwicz approach is to introduce a coefficient of optimism which permits the decision-maker to make some rating, between 0 and 1, which he assigns to the maximum payoff in respect of its chances against the minimum payoff. This, of course, is back to the field of subjective estimates.

Another approach which attempts to provide some method of valuing the possible outcomes is that offered by Savage. This is the approach of the bad loser. It is based upon the attempt to minimize the maximum regret felt should the outcome prove unsatisfactory.

Decision and the Organization

Some people advance design rules which are, in effect, decision rules. Of these the most obvious concerns the use of precedents. This is implicit in Booker's paper. EDER and GOSLING (1965) make it explicitly. This is a 'play-safe' rule which, although creditable under many circumstances, in other situations cannot be satisfactory. For example, in attempting to make radical changes to prepare for decades ahead it would be useless to operate so. Decision rules must fit the occasion.

Eder and Gosling also list some criteria of decision for the aircraft, automobile and marine engineering industries. These criteria they characterize, according to industry, as the relevant design philosophies. This would suggest that differences in decision criteria might be found according to the industry, according to the company in the industry, and according to the design group within a given company.

Since most present-day design takes place within organizations it is useful to have some idea of the way in which an organization may influence design. The most obvious effect of the organization is the part played by the structure. More points at which decisions have to be taken or questioned mean more time taken. More points of question mean, generally, more reasons why not. The larger the organization the less the concentration of adequate information, unless great care is taken. It is probably to combat difficulties of this kind that people tend to adopt a 'project' or 'organic' type of grouping for the introduction of new schemes. Only when the bases of decision are clear does it become possible to use the more common 'matrix' or functional structure. Structure is not all, since attitude determines whether structure will work adequately.Structure can be seen as a facilitating device.

Decision-making is a management operation. Big decisions need close contact with the relevant level of management. Innovation and, particularly, creative design tend to bring about decisions in their own right, which may lead to tensions between the designer and management.

In an attempt to bring together some of the factors which have been considered in the development of attitudes to decision within a design organization *Table 16.1* is offered. This table allows for designers to be of any of the possible types: of the first kind – rational, rational/intuitive, or intuitive; of the second kind – pessimistic, steady, or optimistic; of the third kind – experienced, experienced with knowledge, having knowledge but inexperienced. For the purpose of the table the third category is not indicated although it may influence attitude. These designers work within some kind of organization having a management system. The designers may co-operate with one another or be in competition; their behaviour depends upon the management policy. Apart from the interdesigner attitude, which will tend to influence decision-making, there will be the inevitable effect of the management attitude. This will be influenced by the manager's state of optimism or pessimism and the way in which this is reinforced or discouraged by overall company attitude and what the market suggests. Together with this must be taken the way in which the manager chooses his approach to decision. Is his approach relevant to the situation in hand?

Conclusion

What this chapter has endeavoured to bring out is the complexity of decision. Some people, for instance HITCH (1957), see all techniques such as operational research, as the art of sub-optimizing, *i.e.* of breaking problems down into pieces which may be made the subject of some kind of rational decision. Hall remarks: 'There is no comprehensive procedure for ... the "grand decision".' There is, in fact, no royal road to design. In this chapter I have presented grounds for asserting that designers need to look at the act of

Table 16.1. Some Possible Patterns Relating Market, Management, Decisions and Design (the effects of competition and collaboration are omitted)

Market situation	Mass/seller's	Mass/buyer's	1-off/seller's	1-off/buyer's
Management approach	Trade-off	Bargain	Judge	Impose or fail to decide
Decision type	Computational	Risky	Uncertain	Subjective
Needed designer attitude	Pessimistic	Steady	Steady	Optimistic
Associated design approach	Rational	Rational/Intuitive		Intuitive

decision in design in much more detail and to study more carefully the way in which individuals behave in relevant surroundings, having regard to the type of design being undertaken; that with careful selection they may improve design performance; that design organizations might derive advantage from a review of their concepts of certainty and their expenditure to gain certainty.

People must come to terms with the idea that design is an activity carried out by human individuals for the satisfaction of human individuals: that decision is, perhaps, the most critical step in this activity and, with creativity, places the greatest challenge upon human performance. We live in a world which, for us, is neither timeless nor limitless in resources. SHACKLE (1961) sees decision as the ultimate effort of imagination. For the designer decision is an imaginative act which balances out the intangibles and uncertainties, and assumes responsibility for the outcome.

PART IV

DESIGN TECHNIQUES

Chapter 17

MODELS IN PRACTICAL DESIGN

S. A. Gregory

Introduction

Without a very full use of models of various kinds design is hardly possible, except for the operation of chance.

In copying an object and in remembering one uses a model; in transmitting information regarding a product one uses a model; in managing the whole operation one uses one or more models. In checking a design, one uses all possible methods of simulation, as noted by BOOKER (1964).

The deployment of models is at the heart of design. Much of recent effort in the practical development of design has been devoted to specifying the details of this deployment in order that computers may be programmed to fulfil some part or the whole of a design operation. Thereby the computer becomes a model of the designer. But, in order that this might be achieved, a very substantial effort is required in the collection of models for the details of each programme.

No design effort is likely to have practical success unless, in his work, the designer has a satisfactory model in his mind of the behaviour of nature, and unless he has a satisfactory mental model of the market.

Within a given technology the essence of skill and experience lies in mastering the relevant practical and theoretical models of the subject and the strategies by which they are interrelated in their deployment. Each technology has its own set of such knowledge and techniques. But among the technologies there is such a wide resemblance, already noted in respect of certain types of model, that a general view of the subject of models is worth while.

Models

The discussion of models and what is meant by them is rendered difficult at the outset by the absence of any comprehensive theory of models, although there are several well-developed regions of thought and discussion concerning models of which account must be taken in any approach. Included are those branches of engineering where people are concerned about conditions of similarity between some small or partial system and a large system (this is considered again later); physics and the philosophy of science as discussed by HESSE (1961, 1963); applied mathematics and the associated branches of problem-solving such as operational research; pure mathematics where TARSKI (1954) sees model-making as a new branch of meta-mathematics. The stage has been reached where no academic subject with pretensions to connection with science can avoid some discussion of models and their presentation, usually in symbolic form. In biology, which deals with systems somewhat more complex than chemical systems, it is usually necessary to consider only analogue or mathematical models, in view of the difficulty of obtaining similarity in any close material sense. The limitations and complexities are discussed by CANGUILHEM (1963) and the range of possibilities illustrated in the compilation of BEAMENT (1960). When behavioural situations are considered, as in

Table 17.1. Some Words Containing Aspects of 'Model' (Roget may have more)

abridgment
abstract
algorithm
alternative
analogue
archetype
arrangement

basis
build

cast
category
character
class
code
computer
concept
conception
conjecture
copy

description
design
draft

eidolon
eidos
epitome
essence
example
exemplar

family
fashion
form
formula
frame

gauge
genus
group
guide

hypothesis

icon
idea
ideal
idol
ilk

illustration
image
imitation

kin
kind

mannequin
manner
map
metaphor
microcosm
mirror
mode
mould

nature

opinion
original
outline

paradigm
parallel
parody

pattern
picture
pilot
plan
principle
programme
prototype

quality

reference
referent
reflection
replacement
representation
resemblance
role
rule

schema
scheme
set
shape
similitude
simulacrum

sketch
sort
species
specification
stamp
stock
structure
style
substitute
supposition
surrogate
symbol
system

template
theory
type

variety
version
view
vision

way

Table 17.2. Uncategorized Functions of Models (relate to Table 17.1 aspects)

adjust
amuse

calculate
check
classify
command
communicate
compare
compose
control

depict
describe
design
determine

encode
enumerate
evaluate
experiment
explain
explore

find
forecast

guide

help

illustrate
imitate

increase
indicate
inform
interpret
investigate

judge

manage
measure

operate
optimize
order

pattern

perceive
persuade
plan
please
predict
produce

reduce
refer
relate
replace
reproduce
resolve
reveal

shape
simulate
sort
specify
state
store
suggest

teach
test
train
transform
translate

visualize

Table 17.3. Suggested Classification

Communication (X to Y)		Problem-solving and decision (operation by X)		
amuse	order	adjust	find	predict
			forecast	produce
depict	persuade	calculate		
describe		check	increase	
	reproduce	classify	investigate	reduce
enumerate		compare		relate
explain	specify	compose	judge	replace
	state	control		resolve
guide	store		manage	
	suggest		measure	shape
illustrate		determine		sort
imitate	teach		operate	
indicate		encode	optimize	test
inform		experiment		transform
interpret	visualize	explore	plan	translate

psychology and sociology, the need begins to arise for hypothetical constructs such as the concept of 'role'. Discussion about the range of models employed in scientific activity has been collected by FREUDENTHAL (1963).

The range of functions of models is not limited by the list given and an attempt to sketch out a fuller picture is provided by *Table 17.1.* The information is then analysed in *Tables 17.2* and *17.3.* The result of the analysis is to suggest that models are used generally in problem-solving and communication. The future development of model theory is likely, therefore, to involve information theory.

'Internal' and 'External' Models

Models may be divided into the classes of 'internal' and 'external'. Internal models are patterns in the head, either preconscious or conscious. These are presumably provided with raw material through the modalities of perception as described by BARTLEY (1958) and developed upon neural nets by some process which is still unclear, but is now believed to have a chemical basis. By some mechanisms, possibly like those hinted at by Newman in Chapter 13, small and insignificant pictures become linked with others to form considerable structures. According to a person's inbuilt facilities and his training and experience the mental process is able to deploy a range of preconscious and conscious problem-solving methods. The individual then carries out some action directly or communicates with others.

Communication with others requires some external model. External models, just as internal models, are representational. They either represent to some degree things or events which exist or are believed to exist or have taken place, or they represent things or events under consideration for the future. External models may be made of any kind of information-bearing or information-yielding 'substance', for example three-dimensional solid objects, graphic models such as plans, word pictures, computer programmes and symbolic statements. Provided they deliver the necessary amount of relational and other information they may work through any of the modalities of human perception. They may be more abstract or more detailed than the original or the final copy or representation. They may be distorted. Provided some specified transformation procedure exists by which the necessary information may be extracted or applied they are satisfactory.

Models may convey information according to a spectrum of situations (rather like the situations in which artefacts are used, as described in Chapter 5), ranging from the technical to the human, or from the 'neutral' to the psychophysical. For strictly technical reasons concerned with the inborn abilities of an individual, visual or concrete modes of communication may have to be chosen rather than semantic or symbolic. On the other hand, in order to provide motivation, conviction, or deep-seated response, some form within a given mode or group of modes may have to be used.

More generally, it is preferable to choose from among the models available, according to the task which is to be attempted. Where a 'neutral' situation exists with not much information, it is desirable to use something which closely resembles the 'real thing'. Thus, with a complex metallurgical process, experiments would be carried out on the actual plant if it existed; if it did not exist an attempt to build a pilot plant should be made. Where it is desired to carry through many transformations in an attempt to solve a problem, mathematical symbolism might be used in view of the richness of mathematical procedures. Where shapes or positions are to be defined to human beings, some optical, or optical plus tactile, mode is found to be suitable. In communicating such information to a machine, punched tape is offered; in carrying 'charged' information to human beings, visual or sound channels are used and several layers of information, both immediate and emotionally symbolic are employed. In such selection, the effectiveness of the choice must be considered in terms of resources available, whether technical, money, time, *etc.* Thus to solve a non-repetitive geometrical problem as in plant layout, a strictly geometrical model method is likely to be used as the first choice. With repetitive situations such as pipework layout, three-dimensional model kits, or more recently a computerized optimization procedure, might be adopted.

For emotively-charged situations, the models tend to be made of, or found in, the same substance as the product is to be made. Sketches serve as models for painting; clay models precede sculpture. For writing, trial passages may be dictated or drafts made, or the ideas of other authors may be borrowed. The design problems of such media tend to be solved in those media and in no other way, except it be in the head. They communicate in their own right.

Technological design problems may be solved in a variety of media and communicated in others. Therein lies much of their difficulty and complexity. To study a technology to effect requires an adequate grasp of the facts of the subject and a working facility with the problem-solving tools and the communication procedures.

Models in Technology

Three principal classes of models appear in technology: material models for problem-solving; abstract models for problem-solving; communication models.

Material Models

These range from the actual plant to various smaller, distorted, or simplified versions. Treatments of the theory have been provided by LANGHAAR (1951), JOHNSTONE and THRING (1957), and PANKHURST (1964). Analogue computers represent a stage somewhere between material models and abstract models. ROGERS and CONNELLY (1960) review aspects of the use of analogue computers in engineering design. Clearly, analogue computers can only operate in certain types of situation, *i.e.* those for which analogues exist; their use eliminates much original information and may tend to introduce irrelevant information. On practical grounds they tend to be restricted to situations of few stages. Material models give factual data.

Abstract Models

These are normally symbolic and employ mathematical or propositional operations. They may often be transferred to computers provided that suitable procedures may be found. The whole range of applied mathematics may be used. Within the field of design the most general attention has been directed to optimization procedures. Introductory treatments are given by ASIMOW (1962) and STARR (1963). More extended treatments of economic analysis for manual operation are referred to in Chapter 18. Abstract models manipulate data but do not provide new factual data.

Communication Models

These have recently been treated by ROSENSTEIN, RATHBONE and SCHNEERER (1964). Some communication models form part of the problem-solving process: thus in mechanical engineering, drawings often serve a dual function; GOSLING (1962) refers to diagrams in electronic system design. The history of engineering drawing by BOOKER (1963) summarizes the development of this art, an art now likely to be on the decline.

The complex task of designing and communicating in a system of the class man–computer–machine is still undergoing development. According to present findings some visual channel from computer to man seems the most fruitful, with digital communication from computer to machine. The man to computer channel appears to be rate-limiting, although this may well depend upon the kind of material being handled.

Transformations Relating Referent and Model

Unless the referent, which may be the original thing or the projected product or a mental scheme, resembles the model in all respects (and this raises problems of definition of the method of comparison) some kind of transformation must be accepted.

Commonly, model transformation is thought of in terms of size: the model may have a smaller mass than the original. If the model is made smaller certain features may have to be eliminated. What are the rules of elimination? How can the information content be reduced? What is meant by information in this context? It is also known that if the magnitude of the model is reduced, some kind of distortion of geometry, or time, for example, may need to be introduced in order to make the model operationally comparable with the original.

Whether concrete models or any other substance is being dealt with, it must be appreciated that, in design, model situations are met which do not involve reduction in magnitude. There are situations in which full-scale models are used. More importantly, situations must be dealt with in which the model – the product – contains more detail and is more concrete than the original. The designer starts with a relatively unformed and primitive conception and builds this up to provide a specification for manufacture. In arriving at this kind of result the designer has to make transformations which introduce detail not previously abstracted from his original. What are the rules for this kind of transformation?

Summarizing the discussion so far, it may be seen that there are three classes of model relationship:

(1) The 1 to 1 relationship
(2) The *n* to 1 relationship
(3) The 1 to *n* relationship

The 1 to 1 relationship is at the back of most thinking concerning models in the representational sense: people tend to like their model to represent the original. Even when the system is transposed from some concrete substance to mathematical symbols or to digital code, people still tend to think in 1 to 1 terms. In many practical situations they are forced to accept an *n* to 1 relationship since every item of the original cannot be taken in or appreciated; nor, for many purposes, is it worth while to reproduce every detail of the original. The human bodily system, including perceptual channels, has built-in devices to protect it from excessive stimuli which might be termed information. People are naturally predisposed to *n* to 1 operation. Under such circumstances it becomes possible for different originals to become related to a single model. This is usually fortunate and time-saving.

Where there is a sequence of reputedly 1 to 1 transformations performed, errors may enter into the overall transaction for one reason or another. This situation is significant in the communication of information and, together with other features, has led to some of the developments of information theory. One conclusion that may be drawn from the theory is that, in order to give an adequate representation at the end of the series of transformations, it is necessary to provide redundancy of information at the input. The amount of redundancy necessary is related to the uncertainty likely to be experienced by the receiver regarding the intention of the communication. For example, if one has a workshop next door to the office and if one knows the foreman well and company rules do not forbid it, one may say: 'Please make me a "deral" 26 inches long from this stuff.' If the company system has to be used, drawings become necessary and a job number as well; but it may still be possible to rely very much on shop experience and practice. If, however, the work must be done by tender outside, then a considerable amount of written information and drawings have to be produced, which is particularly complicated in this case because there is no British Standard Specification for 'derals'.

Information and Uncertainty

It must not be taken for granted that the essence of representation is that the model should contain the same amount of information as the original: this only holds for the 1 to 1 relationship. For the *n* to 1 or 1 to *n* transformations changes should be expected in the information content having some relationship to the transformation ratio.

In the development of information theory Shannon (see BRILLOUIN, 1962) preferred to use uncertainty as a measure of information content: in a situation of much information there is little uncertainty and *vice versa*.

The difference in previous history between individuals makes it extremely difficult to have much assurance about the correct transfer of information between them by any model. Practical experience indicates that the more realistic the model the greater the likelihood of satisfactory transfer. The material model is likely to be more successful than the abstract model. The material model is likely to reduce the number of degrees of freedom and hence the uncertainty. A model which contains more information than the referent may, in fact, introduce uncertainty.

With certain classes of system it is possible to define rules of operation in such a way that models in those classes may be comprehended by people of different kinds and backgrounds. It would seem that the essential feature of any such operation is to exclude uncertainty by elimination of unnecessary degrees of freedom. Much of the development of the physical sciences since the time of Galileo has been concerned with either simplification for the purpose of experiment or the development of theory. At the extremes of modern physics we are concerned with rules of information: Einstein has provided rules of measurement to provide observers with the same information; Heisenberg's principle implies that the amount of information in a system must exceed the quantity which it is hoped to withdraw.

In engineering work, when an *n* to 1 transformation has to be carried out, a level of relevance of information must be established. This is by no means easy. It may be convenient to think in terms of some kind of system level, for example the Boulding degree, or the number of physical dimensions. Usually one tries to use the simplest system possible and then add extra information from the stock available. As it were, one overshoots in the initial reduction.

In constructive situations, where 1 to *n* transformations are to be carried through, 'filler' information must be provided. This may come from standard procedures or may have to be prepared for the occasion. Within such constructive situations a number of different models are employed:

(1) The scientist's model of the relevant parts of the universe; the scientist may be a physicist, chemist, biologist, sociologist, *etc.*

(2) Mathematical models and logical models by which the scientist's information, and any concepts which may have become associated, can be manipulated.

(3) Experimental models which may be set up to give extra information at minimum cost.

(4) Pilot plants and prototypes.

For the engineer, the uncertainty reigning in each of the model situations leads to the need for some risk to be taken in practical work. The taking of risk requires decisions by the person responsible. The lack of correspondence between the model and the original may therefore be seen as a large contributor to the development of the decision function in engineering. At bottom it derives from the limitation of material resources and from the human requirement to simplify in order to be able to deal with situations.

Material Models and Design

Material models, *i.e.* models which are not abstract or symbolic and bear some close relationship to the referent in terms of substance, tend to be used either where they are very cheap, or where the mathematical models have not been adequately developed, or where information has not been isolated.

Where a plant or system is in being, the effect of variations of conditions on the system can be determined, provided that these variations do not upset overall production beyond some acceptable limit. These changes can be related to small material models of the system or to models set up on suitable analogues (probably an analogue computer today) or to models on a digital computer. In this kind of situation, only the details which appear to be practically significant need to be put in, gradually building up the models to account for more details.

Where operating plants or systems do not yet exist and information for design is required, a decision must be made on the best means of providing the information which will diminish the possibility of financial loss to some acceptable figure in the given situation. Since there is no operating system, some model system must be established which adequately resembles the large-scale system in mind. This raises the problem of similarity and its cost, which is discussed by KLINE (1965). The analysis of similarity is aided by the use of dimensionless numbers and a substantial list of these has been provided by BOUCHER and ALVES (1959, 1963).

To obtain similarity becomes increasingly difficult as the levels of greater complexity in a hierarchy are reached, for example, in passing from static mechanical structures to dynamic systems.

Mechanical systems have been investigated by physical models for a long time. Structures and stress analysis are readily treated with such models. Today digital computer programmes are available for many practical situations of this type. The inception of vibration increases the difficulty but it is still possible to undertake useful work with cheap models. MORLAND, ATKIN and GANULES (1965) have given some practical examples, particularly relevant to an area just out of reach of easy digital computer practice.

Flow systems have many complexities. This is outstandingly so for situations which involve turbulence, erosion, waves, or roughness. Physical models are actively used to deal with such situations, for instance dams and barrages, waterways and harbours, and for wind effects on structures of all kinds. This, indeed, is the classical area of testing by models.

Heat transfer studies by models introduce problems which may concern time where conduction is concerned, or incompatibility of mechanism where convection is concerned. For this reason there is a tendency to approach heat transfer studies by way of analogue devices.

Chemical reactions often involve complicated systems, not readily treated by models. Clearly, people dealing with the design of chemical and allied process plants have had to devote much thought to their difficult task – made more difficult by the high rate of development of new processes which differ markedly among themselves. Good discussions in this field are provided by: Johnstone and Thring, who look at the problems of similarity in general and in terms of combustion and chemical engineering; contributors to the Institution of Chemical Engineers publication edited by PIRIE (1957); contributors to the Iron and Steel Institute symposium (1965) which dealt with problems of combustion, metallurgical and chemical engineering. The aim of any pilot plant needs to be clearly established. It is a step in an overall design operation.

Biological systems might, in principle, be more complicated than chemical systems, but in practice this is not so because of the relatively narrow range of life conditions. However, with human systems there come the psychological effects discussed in Chapter 5. PAGE (1964) considers the investigation of human environments by models. The contribution of Sheffield to model studies cannot go by without acknowledgment. Electrical systems do not lend themselves to material model investigations although electrical analogies are frequently used for non-electrical systems.

Mathematical Models

For certain primitive and frequently occurring situations it is possible to use abstract symbolic models. These are situations in which the relationships between the parameters may be expressed by equations or other symbolic expressions. Manipulation, within the limits of mathematical possibility, may then take place.

Frequently, in order to achieve a model, serious simplification has to be carried through. A fairly general idea of the use of mathematical models is given by BELLMAN and BROCK (1960). They say: 'Problems may be divided roughly into three types. These are the *natural* problems arising in the world about us; the *model* problems, which we immediately recognize as an element of a class of similar problems; and, finally, the *symbolic* problems where an analytic formulation already exists. To solve a problem by mathematical techniques, we transform it step-by-step from a natural problem to a model problem and from a model problem to a symbolic problem. Obtaining the solution of the symbolic problem in analytic terms, we must interpret it suitably to obtain a solution of the model problem and then go from here to the natural problem. None of these steps is trivial and each requires experience and skill.'

It is important to note the part played by judgment in the handling of the requisite models. In principle, provided the necessary differential equations can be set down and the boundary conditions supplied, any problem can be solved to any level of accuracy required. In practice there are various restrictions: unsolvability, inadequacy of information, and inability to compute either for technical or economic considerations.

An undue enthusiasm for mathematical models and a disregard for data-giving situations is seen as one of the current faults of academic technology. FIRTH (1965) says: 'At the present time.... the designer sees an ever-growing mass of allegedly scientific models, usually described in mathematical terms, purporting to represent the designer's reality, but in fact embodying no confirmation of such either in a rig or in an actual machine. Designers are very familiar with papers carrying titles which lead the designer to suppose that what is contained therein has a direct bearing on his reality, only to find that the title bears little relation to the contents.... A paper, for instance, on the design of hydrostatic bearings which contains a mathematical model of what purports to happen on a slideway or in a bearing, containing no indication that experiments have confirmed that the model accords sufficiently well with reality for the designer to use with impunity. Again, a paper on the characteristics of a variable speed epicyclic gearbox might turn out to be a series of equations which have solutions only in the sense that the real characteristics of both gears and hydrostatic transmissions are ignored.'

This tendency to overplay mathematics may come from a widespread belief in the 'reductionist' approach to technology and the sciences. According to this view any technology is but the application of some science. Therefore it is only necessary to look at the science to which the technology may be 'reduced'. But among the sciences biology may be reduced to chemistry; chemistry may be reduced to physics; and physics may be reduced to mathematics. Hence, and without any qualms, mathematics is at the basis of everything. An associated view may be traced back to the Pythagorean Brotherhood, and to Plato who has been principally responsible for the anti-empirical approach imposed in universities.

For mechanical engineers an introductory note upon the use of mathematical models in design is provided by TRAYSER and CRESWICK (1962) and MITCHELL and CRESWICK (1963). The latter contribution describes the two major types of models as either simulating or tracking. Their methodology of use includes the following five steps: *(a)* initial broad planning; *(b)* derivation of descriptive equations; *(c)* choice of model form; *(d)* determination of model parametric values; *(e)* evaluation of model validity. In their comments upon the derivation of descriptive equations they allow for *(i)* the classical or conventional equation system, *(ii)* the network theory approach which they see as particularly useful for handling complex problems in a systematic manner, and *(iii)* the assumed mode approach.

Optimization Models

A great deal of design is concerned with optimization. For this reason the new texts on design place considerable emphasis on the range of normal mathematical methods. In some cases it is possible to arrive at the optimum by perceiving a discontinuity.The normal approach is through differential equations to obtain a maximum or a minimum. If need be Lagrangian multipliers are used. An alternative approach may be by network theory employing fixed values, inequalities, or probabilities. Both Asimow and Starr provide elementary approaches.

A great deal of modern effort in the development of optimization models has been concerned with the attack upon adaptive control systems centred upon digital computers. A typical source of current information is provided by the 1965 American Institute of Chemical Engineers – Institution of Chemical Engineers symposium.

The Relationship between Classes of Models

Together with the two classes so far mentioned (the fact-giving material models and the information-manipulating mathematical models) practical design uses other classes of models. These are *(i)* analogue models, *(ii)* digital computer models, and *(iii)* general problem-solving models.

A simple way of showing some of the aspects of the relationships is provided by

Figure 17.1. In this figure, which shows a pyramid in plan view, material models are set at the side opposite to symbolic models. Analogue models lie between these two sides; so do digital models. At the apex of the pyramid are the simplest systems, such as static structures. These may be investigated geometrically (the simplest kind of analogue) on paper, or by the equivalent symbolic systems. Given a little more complexity, it pays to go to experimental stress analysis on a suitable model or to make network calculations which are easily transferred to digital computation should the opportunity offer.

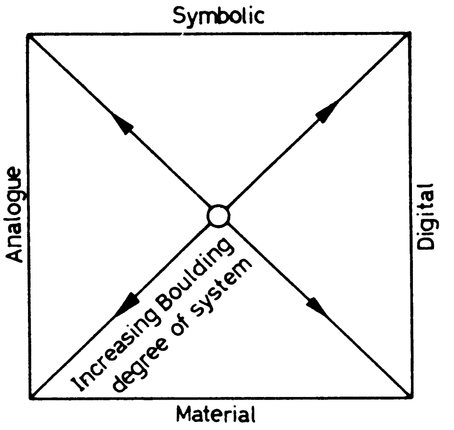


Figure 17.1.
Plan view of model relationship pyramid

At the base of the pyramid are the complex systems of high Boulding degree. Here the distance between model systems may be greater.

The Watts model of the autonomic designer, as in Chapter 11, may be conceived as passing along the axis of the pyramid and tending to use the material nearest to hand. This will always be simpler than the model represented by the surface of the pyramid.

In order to deploy his efforts to the greatest effect, the iconic designer will need to carry the most general strategies. It is at this point that the general problem-solving models need to be recognized. The greatest range of analogues is likely to be provided by general systems theory. The best developed techniques of problem-solving are likely to be those of mathematics. DESCARTES, in his first known publication *Rules for the Direction of the Mind* provided some hints which are still valuable. A more recent approach comes from POLYA (1945, 1954).

Computers and Design

Analogue computers, particularly those based on modular electronic systems, have a facility for dealing with relationships of a continuous character and show considerable advantages in the case of non-linear behaviour. They provide good visual display and easy modification of parameter values. Most practical development is however devoted to digital computers and the models which may be built upon them. Digital computers have great intrinsic flexibility and possess the advantage of substantial memory, the magnitude of which depends largely upon economics.

Digital computers have intrinsic rules of operation which demand the presentation of data in discrete units. Generally, differential equation models require special handling whereas network models based on discrete points lend themselves to digital computer operation.

The most straightforward application in design is for items such as rigid structures of an elementary character for which there is a frequent demand for calculation. Many programmes tend to be readily available in this class of design problem. The interchange of others will help to develop this region and its neighbours.

The more complicated the system and the higher the Boulding degree the greater the difficulty in computer application; but it is with systems of this character that considerable advantage is to be expected. MORTLOCK (1964) has described how it becomes possible to investigate the behaviour of large electrical networks by digital model. In process industries, such as oil refining and chemical manufacture, the application of the digital computer makes it possible to model reactors and systems of reactors. YOULE (1963) has described the hierarchical nature of such models. He says: 'Individual molecules collide and react in the chemical reactor which was part of the chemical reactor described above, and that plant itself is part of a production complex which is part of the activities of a large chemical concern, whose proliferating ramifications form part of a possible model of the whole national economy.

'Out of this serial succession of possible models, only a few at present repay mathematical and computer study, the others being over-complicated. We usually cannot attempt to calculate the effects of molecular collisions, and the simplest useful manageable model is that of the reactor. For this, with the aid of physical chemistry and chemical analytical techniques, and with the help of a statistician in planning the experiments, we are able to set up a reasonable mathematical model. This can then be embedded in the larger model of the whole plant.'

The combined model of the reactor and the whole plant may be used in setting up a control system for the plant, or if incorporated into a model of the firm as a whole it lends itself to the study of new venture propositions.

BYRNE and VAN KOOTEN (1965) discuss two ways in which models of reactors have been obtained. One was developed from theoretical considerations; the other was obtained by working back from the practical data from suitably conducted experiments on the plant concerned. Optimum behaviour is calculated by using linear programming based on considerable approximation of the reactor models.

Instead of modification of the plant conditions by human operators on the basis of computer optimization it is possible to have the computer issue direct signals to mechanical or electrical controls on the plant. In such a situation the computer is actually making modifications in the process. This is tantamount to a marginal redesign, which is in the process itself, but not in the hardware which encloses the process.

The greater participation of computers in design depends upon the considerable improvement of the means of communication between designer and computer, and much greater immediate flexibility of the computer accompanied by suitable visual displays. These needs have been appreciated for some time and the most attractive development in this area is 'Sketchpad' as described by SUTHERLAND (1963) at the Spring Joint Computer Conference, at which several other allied developments were discussed.

What would be most valuable for many practical parts of design appears to be the genuine three-dimensional display with facilities, rather like those of the electronic analogue computer, for feeding in and modifying lines and similar features. This is something to look forward to.

It would seem that, although manipulatory procedures of this kind might be obtainable, great difficulty will be found in attempts to set up programmes for creative behaviour or general design problem-solving behaviour. MINSKY (1961) notes that: 'It is very difficult to take apparently common-sense procedures, such as those described in Polya's books on practical heuristics in mathematical problem-solving, and put them into machine-usable form.' Against this should be set the work of SIMON *et al.* (1958, 1962) and NEWELL (1963, 1964) in relatively restricted fields. SHUBIK (1964) has more recently stressed the difficulty of codifying very general problem-solving strategies. Beyond this MACKWORTH (1964) has emphasized the even greater difficulty of problem-finding.

Models and Creativity

Central to a creative performance in design would appear to be the possession of skill and facility in the manipulation of the most important models within the specific branch of technology. It might also be thought that skill with very general patterns of problem-solving would be of prime significance. This, indeed, gains support from the work of GUILFORD (1959); but one might also expect that such skill could be largely wasted unless adequate models of the situation prevailed.

Since most design work is evolutionary in character the first level of creative skill might be seen in the flexibility and fluency in handling first-level models, *i.e.* models immediately related to existing products. The 'schema-scrambling' discussed by Broadbent in Chapter 14 would apply here. What is needed is facility in devising, hunting down, or applying the less obvious variations applicable.

The Synectics group seem to rely on biological analogies for many of their approaches. Perhaps this class of models is chosen since it comes from a range of systems having a greater degree of variation than is possible with the simpler mechanical systems. But this is a variation, or class of variations, which tends to be more relevant to fields which have been considerably explored, particularly in terms of mechanical gadgets. Other people have found metaphors a good natural source of distortion of schema.

It is the attempts to escape from prevailing major concepts, usually system concepts which carry their own apparatus of organization and obedience, which seem to need rather different models. These are the simplified models which permit the generation of completely new system structures; structures now possible because the old linkages are dissolved away by the process of thought. This may be helped by a change of circumstance or a lapse of time.

However, in the process of thought there has to be some reorganization of mental programmes, the models of procedure. EVANS and NEWMAN (1964) have produced a speculative model of the process of dreaming, based upon analogy with computer operation, which suggests that dreaming is a process which is necessary for the elimination of 'junk' from the mental computer system. In Chapter 13, Newman speculates about the nature of the aesthetic experience and suggests that it comes from the satisfactory match between the thought processes and the object. It has been noted, however, that much creative work comes through difficult and troubled thinking and some from 'incubation'. This recalls the earlier speculation on dreaming. Might not incubation play the same part in creative work as dreaming plays in normal life? Incubation, according to this view, is concerned with the cleaning up and regeneration of the mental programmes and the essential simplification of basic concepts and the preparation of new interrelationships.

If this model has any validity it may have considerable practical repercussions. As far as is known, present approaches to the development of creative potential and to the exercise of schema-scrambling depend upon short-term operations, and upon the ability to produce answers in restricted periods of time. Perhaps, because of this, their success is only in terms of trivialities. For major creative operations it might be that the suggested deep-down and radical process is necessary.

The working models of creative behaviour may be wrong. To achieve greater success in the art of producing radical new ideas – the field of 'antithetics' – new models may be needed.

Strategies of Model Deployment

The practical skill of the designer lies in his deployment of the different kinds of model. ARCHER (1965) notes that: 'Engineers may be weak in the systematic construction of the brief and in searching for original design ideas, but they are strong in the techniques of the development of detail'. These techniques are, of course, model techniques. Archer recommends that the most general models should be used in the opening stages of design for the development of concepts, and that the most detailed models should be used at the end, both for the design activity as such and for communication. This is shown by the Watts model of the designer.

But although one may stipulate a very general approach, as discussed by GREGORY (1966), which has the merit of including more potential solutions within its 'catch' and going to the limits of the bounding system, there is also the need to be intensely practical. There is, indeed, a continual requirement to reinforce the broad concept with practice. There is a dialectical interplay between the manipulative model and the fact-giving model.

The kind of generality possible depends upon the state of development of the system, its complexity, and its Boulding degree. It also depends upon the more usual components of the design situation. In addition there are the obligations which help to determine strategy: *(a)* the need to complete the design – the work must proceed; *(b)* the need to design with limited resources – every avenue cannot be explored and those most likely to yield results according to experience must be chosen; *(c)* the need for the product to work.

Since paper studies tend to be cheaper than fact-giving studies, particularly in the case of the more complex systems, the critical discussions centre on the reasons for constructing pilot plants or prototypes. This merits a discussion of its own, but most of the points are raised in the Iron and Steel Institute Symposium on Pilot Plants (1965).

Practical Outcomes

There is now substantial agreement about the significance of the different classes of models in design, both for problem-solving and communication. What is still to be decided is whether the models and the methods of using them can be improved. What about the poorly developed areas of search and selection? Are the best techniques being employed, or may they be improved? By how much should disciplines come before data? What, in fact, are the important disciplines? These are the kinds of problems which may be tackled by suitable research.

There are also the larger models, the general models of problem-solving and the models of the designer; and models of creative behaviour. It is against such models that practical achievement may be set, and from validated models that new educational procedures may be developed.

In Chapters 18–21 the opportunity is given of looking at the use in design of two technical procedures, the use of economic analysis, the use of computers, and two complete design sequences. The first of these is a typical industrial design operation carried through without self-consciousness and dedicated to a practical outcome. Its value lies in the way it shows a varied deployment of models. Then an example is given of a design carried through in a special educational situation. This was intended not only to give a practical design but also to aid the designer to restructure his mental model of design as a whole.

Chapter 18

THE IMPLICATIONS OF ECONOMICS IN ENGINEERING DESIGN

A.P. Shahbenderian

Introduction

The commercial success of an engineering design (whether of a large-scale plant or individual product) depends largely on the technical, economic and aesthetic merits of the design, and although these merits can to some extent be judged independently, the design process itself involves a close study of the complex and dynamic interrelationship between them. Even a superficial examination exposes this interrelationship between the technical, economic and aesthetic aspects of design. For example, a technically efficient design often leads to profitable manufacture and the lack of aesthetic merit can cause commercial failure, particularly in the case of consumer goods. Conversely, the desire for high technical merit in a design can raise subsequent production costs to a point where financial success is endangered. The successful design is therefore a compromise involving an optimum combination of technical, economic and aesthetic merit. This optimum combination can be arrived at qualitatively or quantitatively by the individual designer or by a large team of engineers, 'designers' and economists. It is undoubtedly successful optimization that has led to the design of such a plant as the Scottish Agricultural Industries fertilizer factory at Leith, or such a product as the 'Mini' motor car, or such buildings as those designed and constructed by Nervi in Italy. Quite clearly there are other factors, such as social and political needs, which can affect the design and manufacture of a plant or product; but in most industrial environments techno-economic design considerations are often paramount, with the aesthetic aspects influencing in a less quantifiable way the eventual design. The 'information flow diagram', shown in *Figure 18.1*, indicates the interaction between these three aspects and their place in the overall design and production scheme.

The arrows in *Figure 18.1* indicate the direction of information (or influence) flow and feedback. Company policy influences design motivation which, in turn, influences a train of. design activities (the design process) involving a study of the interrelated technical, economic and aesthetic aspects of the design. The result is a designed product or plant. The product or plant is then normally manufactured, and eventually either the product is sold, the plant is sold, or the plant manufactures a product which is sold. A market analysis of the projected sales can then give rise to feedback information which, in turn, affects manufacture, design process and company policy, as indicated in *Figure 18.1.* The influence on company policy is such that fresh motives may be created for evolutionary (improved) or radical (novel) design. The design process therefore depends on the dynamic interaction of those factors indicated in *Figure 18.1.*

In many industrial design schemes, aesthetic aspects are quite frequently severely curtailed by technical (*i.e.* functional) demands

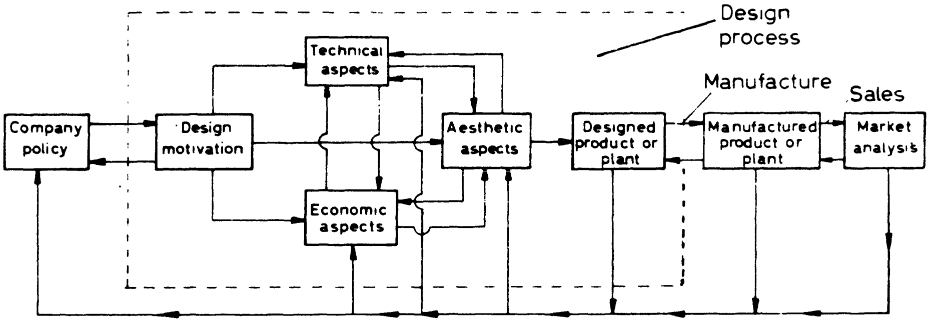


Figure 18.1. Information flow diagram

and, in a purely industrial environment, it is often permissible to consider them as implicit in the technical design. Since this chapter is essentially concerned with engineering design in an industrial environment, the discussion is henceforth limited to design problems of a purely techno-economic character. The 'technical aspects' indicated in *Figure 18.1* are taken to include:

(1) Conventional design techniques.
(2) Evolutionary design techniques.
(3) Radical design techniques.

These technical aspects are discussed in conjunction with economic aspects involving a consideration of:

(i) The economic environment.
(ii) The type of economic objective function.
(iii) Overall economic optimization.
(iv) Economic sub-optimization involving:
  (a) Fixed costs alone.
  (b) Fixed and variable costs.

Conventional Design Techniques

By conventional design is meant the design of a plant or product using existing knowledge and established practices. Most industrial design processes fall into this category and the successful design depends on a proper study of the technical factors and of the particular economic environment; the final design depends strongly on the chosen economic objective function. In general, the problem also arises of whether overall or sub-optimization is to be used.

The Economic Environment

The economic environment in which a company operates conditions the policy of the company, and company policy in turn influences design motivation. For example, the design of a food processing plant or pharmaceutical factory for an underdeveloped country is likely to be different from the design of a plant producing similar products in a highly industrialized country. In underdeveloped countries having a planned and labour-intensive economy, the incentive will be to design factories that will operate with a large labour force (for social as well as economic reasons). Batch and manually operated processes are likely to be favoured rather than continuous fully-automated processes. Furthermore, the optimum life and size of plants will differ in underdeveloped and industrialized countries (SHAHBENDERIAN, 1963) due to the differing cost of maintenance and repair and differing restrictions on capital expenditure. The nature of the manufactured product is also likely to differ due to different social attitudes and economic needs.

The so-called planned obsolescence of consumer durables also extends to the design of entire plants – particularly chemical, in which the rate of technological improvement is so rapid that the process (rather than the equipment) used becomes obsolete in a relatively short time.

The Type of Economic Objective Function

The optimum conventional design is affected not only by the economic environment but also by the type of economic objective function used. For example, if the design of a complete plant rather than of a particular engineering product is considered, the optimum *size* of a plant (*i.e.* capital investment involved) will depend on the objective function chosen. As shown in *Figure 18.2,* the optimum investment for a typical sales and cost pattern depends on whether profit, percentage return on investment, or venture profit is chosen as the objective function.

There is a tendency nowadays to use more sophisticated economic objective functions,

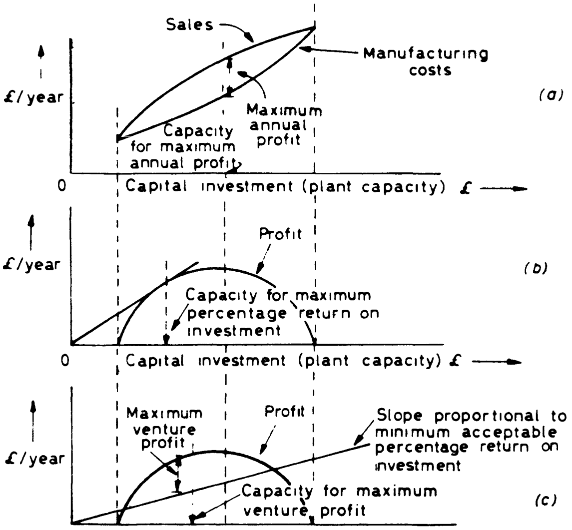


Figure 18.2

such as present worth, venture worth (HAPPEL, 1958), interest rate of return, *etc.,* using discounted cash flow techniques. In general, the use of each function leads to a different optimum capital investment for a particular plant, and this in turn defines the equipment design capable of operating economically at the optimum capacity level.

Overall and Sub-optimization

The above discussion on the influence of the economic objective function presupposes that at each plant capacity level an economically optimum design has been made of every component of the plant, with each component linked together to form an integrated, functional and profitable complex. It is very often possible to design individual components for optimum techno-economic performance (*i.e.* to carry out a sub-optimization) without reference to other components in the complex design; but quite often the linking together of sub-optimized components produces an overall design that is less profitable than a plant that has been designed on the basis of an overall economic optimization. In general, overall optimization techniques should be used whenever possible and a point on the manufacturing cost curve shown in *Figure 18.2(a)* should be minimal at any particular investment. The following example of a reactor–separator system design (based on that of KRAMERS and WESTERTERP, 1963, and already published in full by SHAHBENDERIAN, 1964) will illustrate this point and show how the objective function influences the design of individual plant components.

Overall Optimization: Reactor–Separator System

A first order reversible and isothermal reaction $A \rightleftharpoons B$ takes place in a tubular reactor as shown in *Figure 18.3.* ϕ_m lb./h of pure A are mixed with ϕ_{mr} lb./h of recycle A before entering the reactor (in which plug flow occurs). The products of reaction pass to a separator where ϕ_m lb./h of pure B leave as bottoms product, and ϕ_{mr} lb./h of pure A are recycled. The nomenclature and example is based on that of Kramers and Westerterp and for the first order reaction considered the reactor volume V_r is given by the equation

$$V_r = -\frac{\phi_m}{\rho k}\,\frac{K}{(K+1)\,\xi_{AL}}\ln\left(1-\frac{K+1}{K}\xi_{AL}\right)$$

where k is the reaction velocity constant, K is an equilibrium constant, ρ is the density of A and B (assumed equal) and $\xi_{AL} = 1 - W_{AL} = W_{BL}$, where W_{AL} and W_{BL} are the mass fractions of A and B respectively leaving the reactor. A numerical calculation has been published by Shahbenderian (1964) in which the following values were used:

$k = 0{\cdot}09\ \text{h}^{-1}$
$K = 10$
$\rho = 60\ \text{lb./ft.}^3$

The production rate ϕ_m was fixed at 100 lb./h.

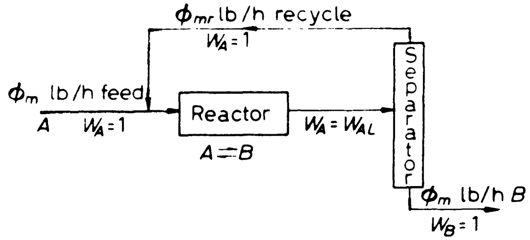


Figure 18.3. Reactor–separator system

Capital and operating costs were specified as a function of V_r, ϕ_m and ϕ_{mr}.

The capital cost I_R of the reactor was assumed to be given by $I_R = £900\ V_r^{0\cdot7}$

The total annual manufacturing cost was compounded and, assuming that B could be sold for 3 d./lb., *Table 18.1* was drawn up

Table 18.1

Yield ξ_{AL}	Reactor volume V_r (ft.^{3})	Total manufacturing cost C (£/year)	Sales revenue S (£/year)	Annual profit P (£/year)
0·4	24·55	7,952	9,900	1,948
0·5	26·88	7,672	9,900	2,228
0·6	30·34	7,555	9,900	2,345
0·7	35·40	7,552	9,900	2,348
0·8	44·89	7,724	9,900	2,176
0·9	86·10	8,811	9,900	1,089

Yield ξ_{AL}	Total capital investment of reactor and separator $I_R + I_S = I$ (£)	Percentage return R on investment (% per year)	Venture profit VP (£/year)
0·4	10,314	18·8	398
0·5	10,636	20·9	632
0·6	11,292	20·8	652
0·7	12,216	19·2	514
0·8	14,050	15·4	68
0·9	21,414	5·1	−2,127

showing the reactor volume, total manufacturing cost and various profitability criteria as a function of yield ξ_{AL}.

The last column in *Table 18.1* shows the venture profit VP, calculated according to the equation $VP = P - R_m I/100$, where R_m is the minimum acceptable percentage return on investment, taken in this example as 15 per cent/year. The venture profit is clearly the excess of actual profit over the minimum acceptable profit.

Table 18.1 shows that if total cost C or profit P are chosen as objective functions then the same optimum design results (ξ_{AL} in the region of 0·7, V_r = 35·40 ft³), but that if percentage return R, or venture profit VP, are chosen as economic criteria then the optimum designs will differ (ξ_{AL} in the region of 0·5, V_r = 26·88 ft.³; and ξ_{AL} in the region of 0·6, V_r = 30·34 ft.³, respectively). Thus the optimum design (*i.e.* reactor volume) of reactor–separator system clearly depends on the choice of the profitability criterion.

Sub-optimization

In the previous example an overall economic optimization was carried out on the reactor–separator system. It would have been invalid to carry out an economic sub-optimization on the reactor alone: for instance it would be invalid to find the reactor volume that gave minimum total operating costs of reactor alone, since this would indicate the smallest reactor possible as the optimum. (This would mean high recycle pumping costs due to incomplete conversion of reactant A and high separation costs in the separator). Thus, in this example, an economic balance between reactor, separator and recycle costs must be calculated on an overall basis; sub-optimization of reactor or separator design does not correspond to the design attained on an overall basis.

There are, however, instances where sub-optimization is valid and the optimum design of plant components can be reached without reference to the other plant components.

The simplest type of sub-optimization problem is one in which annual operating costs can be ignored and only capital costs (*i.e.* fixed annual costs) need be considered. A typical case is pressure vessel design as given by Happel. The following simple example on the optimal design of tin cans also illustrates this point.

Fixed Costs Alone: The Optimal Design of Tin Cans – In the manufacture of closed cylindrical tin cans using tin plate of a given thickness, it is necessary to minimize the area of sheet metal used. (*i.e.* the capital cost of metal).

If the diameter and height of the can are D and H respectively then, for a can of fixed volume V

$$V = \frac{\pi D^2 H}{4} \qquad (18.1)$$

The area of sheet metal required is given by A where

$$A = \pi DH + \frac{\pi D^2}{2} \qquad (18.2)$$

or, from equation 18.1,

$$A = \pi D \frac{4V}{\pi D^2} + \frac{\pi D^2}{2} \qquad (18{\cdot}3)$$

Differentiating with respect to D and equating to zero in order to find the minimum area required, gives

$$\frac{dA}{dD} = -\frac{4V}{D^2} + \pi D$$
$$= 0$$

Thus, if D_0 denotes the optimum value of D, then

$$D_0 = \left(\frac{4V}{\pi}\right)^{1/3}$$

Note that $d^2A/dD^2 = 8V/D^3 + \pi$ which is positive and thus corresponds to a minimum value of A. Therefore, using H_0 to denote the optimum value of H

$$H_0 = \frac{4V}{\pi D_0^2} = \left(\frac{4V}{\pi}\right)^{1/3}$$

Therefore

$$\left\{\frac{H_0}{D_0}\right\} = 1$$

Thus, if the volume of a can is specified, the area of tin plate required is a minimum when the can diameter equals the can height.

MALLYA, KING and EILON (1964), in discussing the optimal design of tin cans, have shown that if seam and trim losses are taken into account in forming the can body and punching out the metal caps from metal plate then

$$\left\{\frac{H_0}{D_0}\right\} = 1{\cdot}24 \text{ to } 1{\cdot}42$$

the variation from 1·24 to 1·42 being dependent on the effectiveness of nesting in punching out the end caps from metal plate.

The optimum design is again realized as a result of a sub-optimization problem in which only the capital cost of the metal plate is involved.

Fixed and Variable Costs — There are many designs resulting from sub-optimization techniques in which both fixed and variable costs are involved. For example, the optimum design of heat exchangers (Happel), the optimum thickness of pipe lagging (Happel) and the optimum design of nuclear reactors (MARGEN, 1960) depend on a balance of fixed against variable costs. Another typical example of sub-optimization is the selection of economical machining rates. BROWN (1962) shows that the cost of a machining operation can be divided into four main items:

(1) The cost of inserting and removing components from the machine.

(2) The cost of the cutting time.

(3) The cost of replacing worn tools.

(4) The cost of reconditioning worn tools.

He then proceeds to minimize total cost for various conditions of tool speed and feed, assuming that the machine tool, the work material, the depth of material to be removed, and the type and angles of the cutting tool are initially selected. If none of these latter variables had been fixed then the problem would have been more complex to take into account the interaction between these variables, together with any other factors affecting the machining rate. It would, in fact, have been more a problem of overall rather than sub-optimization.

Evolutionary Design Techniques

Using conventional design techniques, *i.e.* existing knowledge and established prac-

Table 18.2

Yield ξ_{AL}	Reactor volume V_r (ft.^{3})	Total manufacturing cost C (£/year)
0·4	22·21	7,865
0·5	24·55	7,581
0·6	27·14	7,431
0·7	32·14	7,426
0·8	40·55	7,580
0·9	78·40	8,611

Yield ξ_{AL}	Reduction ΔC in C (c.f. Table 18.1) (£/ year)
0·4	87
0·5	91
0·6	124
0·7	126
0·8	144
0·9	200

tice, it is possible to arrive at an optimum design based on an appropriate economic objective function. It is then interesting, and often advantageous, to investigate the direction in which the design is likely to evolve as a result of changes in the technical or economic parameters. This exploration into a techno-economic region that is at present unattainable may be called evolutionary design.

Consider, for example, the reactor–separator system discussed previously. It is interesting to consider how the overall optimum design would change as a result of changes in the technical or economic parameters. Such parameter changes might involve expenditure on research or development, on improved management or sales techniques, or on superior raw materials. Consider, for example, the implications of a 10 per cent increase in the value of the reaction velocity constant k, from 0·09 to 0·099 h^{-1}, due to (say) the discovery of a new catalyst or the purchase of a superior catalyst – without any increase in the cost parameters.

Table 18.3

Yield ξ_{AL}	Total manufacturing cost C (£/year)	Reduction ΔC in C (£/year)
0·4	7,817	135
0·5	7,528	144
0·6	7,397	158
0·7	7,377	175
0·8	7,518	206
0·9	8,485	326

The new reactor volume V_r required and the resulting total manufacturing cost would then be shown as in *Table 18.2* (compare this with *Table 18.1*).

The final column in *Table 18.2* shows the reduction in total manufacturing cost that would be brought about by the improved catalyst.

Table 18.4

Yield ξ_{AL}	Affect of 10 per cent increase in k. Reduction ΔC in C (£/ year)	Affect of 10 per cent increase in sales price. Increase in revenue (£/ year)	Affect of 10 per cent decrease in I_R. Reduction ΔC in C (£/ year)	Affect of 10 per cent decrease in raw material prices. Reduction ΔC in C (£/ year)	Affect of 10 per cent decrease in labour and overhead costs. Reduction ΔC in C (£/ year)
0·4	87	990	135	165	300
0·5	91	990	144	165	300
0·6	124	990	158	165	300
0·7	126	990	175	165	300
0·8	144	990	206	165	300
0·9	200	990	326	165	300

Thus, restricting the discussion to changes in total manufacturing cost C, a 10 per cent increase in k has the effect of reducing the optimum total manufacturing cost (at $\xi_{AL} = 0 \cdot 7$ as before) by £126/year.

Changes in economic parameters can also be investigated assuming the value of the technical parameters (k only in this case) to remain constant. Thus, for example, the reduction in capital cost I_R of a reactor of volume V_r, from $I_R = £900\ V_r^{0 \cdot 7}$ to $I_R = £810\ V_r^{0 \cdot 7}$ (10 per cent reduction) would lead to the cost changes shown in *Table 18.3* (again compare this with *Table 18.1*).

The total cost is again a minimum at $\xi_{AL} = 0 \cdot 7$ and the reduction in C is £175 for a 10 per cent change in the capital cost function. The economic implications of independent changes in k or I_R have been demonstrated in *Tables 18.2* and *18.3*. It is conceivable that improved values of k can *only* be obtained at the expense of an increase in values of I_R (*i.e.* increased capital costs); but a study of the effects of these independent variations is a very useful preliminary guide to the amount of money that can be spent – either on evolutionary design and development or on improved materials. The financial implications of improved technical design can also be compared with, for example, the economic advantages accruing from reduced raw material costs as a result of better purchasing efforts. The influence of a reduction in labour and overhead costs can also be assessed.

It can be seen from *Table 18.4* that even these limited independent variations furnish a greater understanding of the feasibility of evolutionary design and the nature and extent of any financial advantages that may arise out of such improved design or cost reduction. It is clear, for example, that a 10 per cent reduction in labour and overhead costs has a greater effect on overall manufacturing cost than a 10 per cent increase in the reaction velocity constant k. Furthermore a 10 per cent increase in sales price per lb. of product would furnish an increase in annual revenue far exceeding any cost benefits likely to accrue from process improvements. A subjective assessment is clearly necessary concerning the possibility and probability of such changes.

Radical Design

There are stages in the design history of most industrial products where evolutionary design reaches a technical or economic limit; for if the designer chooses an inherently poor system in the first place, techno-economic optimization only helps him make the best of a bad situation. The need for radical (*i.e.* completely novel) design usually arises in a forward-looking organization, but engineering designers are not always aware of the propitious time to discontinue evolutionary design. A paper by STARKEY (1964) touches on this aspect. He discusses the influence of economic factors on the commercial design strategy of cathode ray tubes. He considers the case where an increase in technical merit of a product of conventional design may reduce the cost of promoting sales but also increase the manufacturing cost. If the sales price of the product remains constant as technical merit is improved, then clearly an optimum (*i.e.* minimum) total cost is likely to exist at some level of the technical merit – assuming that technical merit has a quantitive significance. There is also likely to be a lower and upper limit to the technical merit, below and above which the manufacture of the product will result in a financial loss. This is simply an expression of the fact that cheap but shoddy goods are unlikely to sell profitably and that it does not always pay to improve too much the design of a particular product. Starkey then considers the economic implications of a product of new design (*i.e.* radical design in the context of the present chapter) and shows that, if technical merit can be improved by effective co-ordination of design effort and if the cost of sales promotion and manufacturing cost can both be reduced, then an optimum technical merit will exist for the novel design, but at a higher merit level.

Although the unit profit arising from the sale of the radical product may be no greater than the unit profit of the conventional product (due to the possibility of lowering the unit sales price of the radical product) *annual* sales and hence *annual* profit are likely to be greater. Furthermore a larger share of the market may, in due course, lower even more the cost of sales promotion.

Naturally, a radical design can only be produced as a result of co-ordinated efforts within a particular organization and any economic advantages that may arise will depend largely on technical innovations. However, the *need* for radical design is always apparent if a proper economic assessment is made of the conventional product design and manufacture, and if the economic limitations of improvement by evolutionary design are recognized.

Conclusions

An attempt has been made in this chapter to show that there is a dynamic relationship between the technical and economic aspects of engineering design and that the successful commercial design of an engineering plant or product depends not only on technical skill but also on a proper understanding of the economic implications.

Chapter 19

THE USE OF A DIGITAL COMPUTER IN DESIGN OFFICES

K.C. Parton

Introduction

The digital computer has now been accepted extensively as a tool for use in design offices. This acceptance, although earlier fostered by the obvious value of the computer for straightforward long arithmetical calculations, has now spread to cover a far wider range of interests. The various functions associated with design offices can be listed broadly as follows:

(1) Designing apparatus to meet customers' requirements.
(2) Detailing the design for manufacture.
(3) Examining manufacturing problems.
(4) Checking test results.
(5) Considering the physical and performance effects of new materials and techniques.
(6) Constant appraisals of all new methods to improve design from the point of view of improving cost, ease of manufacturing, efficiency, noise, and general appearance.

In all of these the digital computer can be of assistance to some degree, but the economical limits of computers in these various functions are now discussed.

Designing Apparatus to Meet Customers' Requirements

The main problem facing any particular group beginning to use the computer will eventually resolve itself into planning the type of programme to be tackled. In general, these can be analysis programmes giving a specific answer to a specific calculation, or any amount of elaboration to synthesis programmes where the computer may, by using logic, rapidly run through the whole series of designs in order to obtain an optimum. *Figures 19.1* and *19.2* illustrate the major differences between an analysis programme for the design of salient pole synchronous machines. The points that emerge from comparison of these two is that the analysis programme does not require anything other than a chosen set of known physical quantities (*i.e.* standard stampings, pole and slot tools and stock copper sizes for existing standard frames). The designer with his own experience of machine design behind him can rapidly choose what he thinks would be the answer for a particular enquiry and feed these into the computer for an accurate performance prediction calculation. Usually several alternative designs are demanded giving results of minor modifications that the designer would like to examine. As this type of programme is extremely fast, easily written and cheap in overall use, it has been found to be extremely popular in a variety of design offices for stock or standard machines and in larger and special machine design groups. Day-to-day usage is consistent.

The extension of analysis programmes into pure synthesis programmes, however, results in very comprehensive programmes which from the management point of view may appear the ideal. Unfortunately, they have in many instances proved not particularly practical in the long run

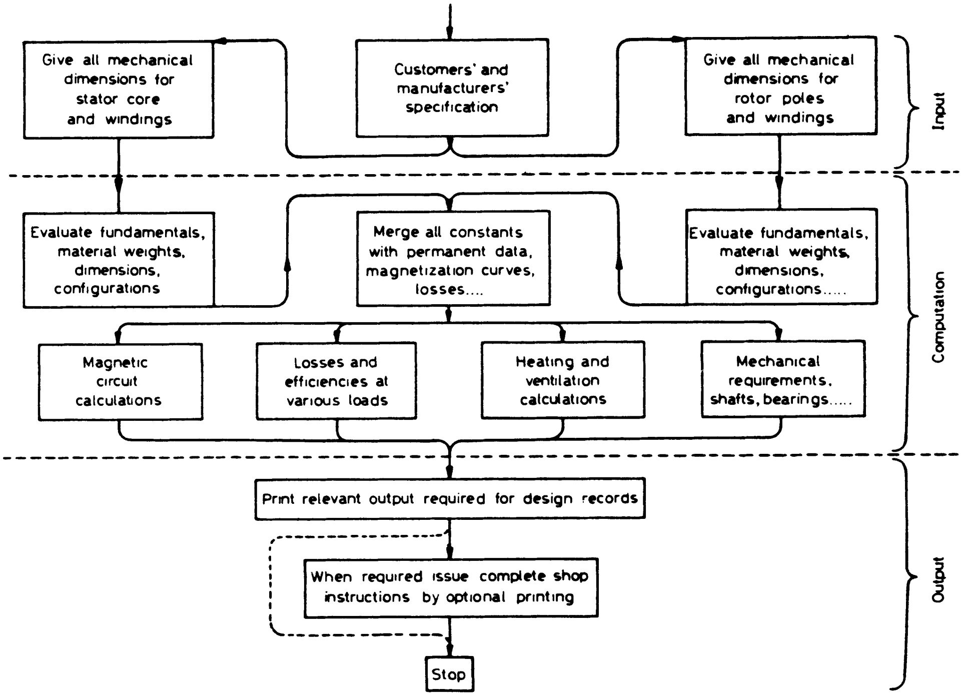


Figure 19.1. General analysis flow diagram for salient pole synchronous machine

and are not used as much as was anticipated. One important technical reason for this has been that even though written with the full cooperation of the designers concerned, fixed tolerances have to be set on many dimensions throughout the programme. However, in practice a designer working individually can at times relax these tolerances slightly when he feels circumstances justify it. This is an insuperable problem as there is always a certain amount of art in design which at times justifies flexible boundaries that cannot possibly be reproduced in automatic synthesis programmes. It thus follows that a good designer working with analysis programmes will in many cases produce a slightly better design than a fully-automatic synthesis programme, and with modern commercial competition this difference may be all important. Synthesis programmes, however, can be extremely valuable in the field of very large machine design where completely non-standard designs are produced, (such as large alternators and transformers) but in general such programmes will be more used in obtaining a quick overall picture than for the final complete design. Thus, one might for this type of machine use a synthesis programme to obtain first sets of likely dimensions and then obtain the best result with a really skilful designer starting from these and working with analysis programmes backed by the organization's experience. For this reason, some of the synthesis programmes used in my organization have provision for rerunning with the previous logical decisions of the computer replaced by data specified by the designer. The problem requires a lot of serious heart searching, as the obvious publicity value of synthesis programmes and their apparent easy understanding by senior management tend to make their advocation more popular than is justified. The time, effort and cost necessary to produce a really error-proof synthesis programme can become very large and must be compared with the likely extra value that would be obtained by spending the same effort in improving analytical techniques.

It must finally be appreciated that whatever decision is reached will have a profound effect on the eventual design methods, overall engineering efficiency and organization of the design office. Furthermore, implicit acceptance of a very general synthesis programme could have a serious effect on the eventual design ability of the office, particularly in developing junior designers.

In my opinion, if the object of the design office is to produce the best possible designs always consistent with up-to-date techniques and materials, there is no doubt that initially the main emphasis must be on the development of comprehensive and really good analysis

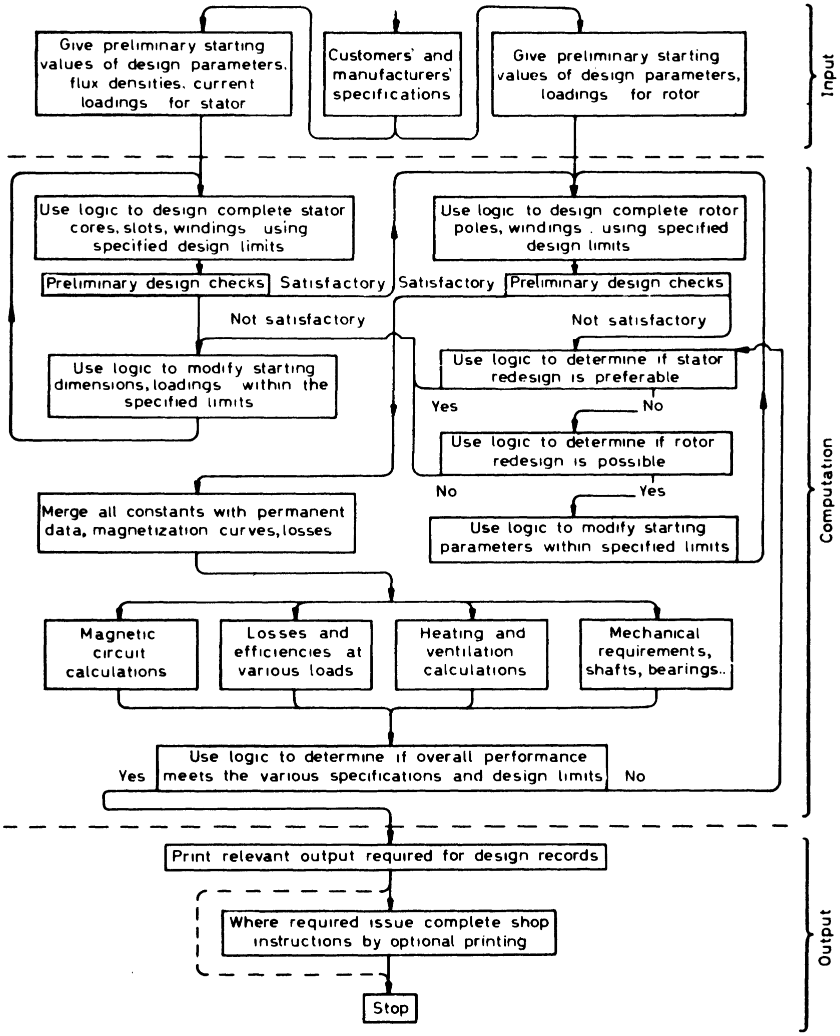


Figure 19.2. General synthesis flow diagram for a salient pole synchronous machine

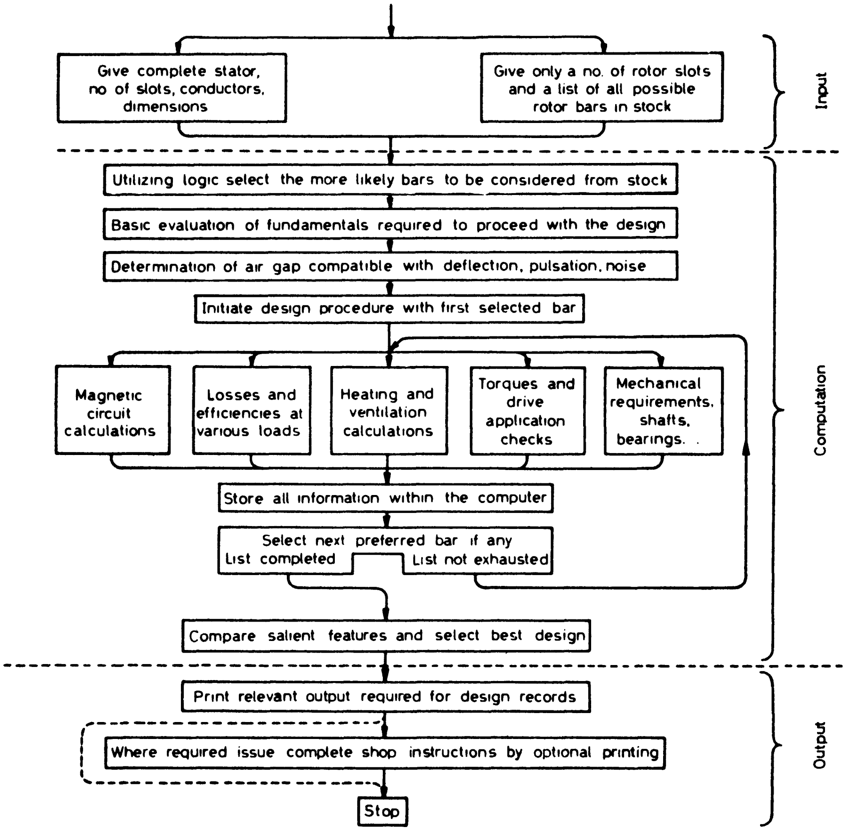


Figure 19.3. A mixed synthesis–analysis flow diagram for squirrel cage induction machines

techniques and programmes. A limited amount of fairly straightforward synthesis can be added as required and is likely to prove the best solution for many items of design. *Figure 19.3* illustrates a typical induction motor design flow diagram of a heavily used programme employing this principal.

In general, a balance must be maintained by which the designer receives the maximum benefit for the minimum computer cost. A rapt absorption in the art of programming to include all the logical intricacies of machine design can be extremely unprofitable. This, however, will naturally be discouraged if a senior designer is actively co-operating in the project throughout.

Detailed Design for Manufacture

Detailed design is a mixture of design office and drawing office responsibilities and involves a mass of routine detailed work that has to be done. For example, in an electrical machine complete details must be prepared of the total length of copper of a certain section that must be requisitioned from the stores, together with careful details and drawings of how to bend it to form the windings, and then the length and type of insulating tape to be bound round it, *etc.* Many details like these appropriate to each design are sent to the shops, requiring the continual preparation of copious detailed specification sheets and drawings. Once prepared, they have to be rigorously checked since any mistakes, particularly on large machines, can lead to very costly scrapping of material, and hold-ups in the production chain if they are not discovered until manufacture has started. The computer is, therefore, being pressed into service to help in several facets of this work:

(1) For various fairly standard items the computer can automatically list all the various sections, component numbers and lengths, *etc.* and these can be arranged to be directly punched on to the side of standard unscaled drawings with lettered dimensions.

(2) Where routine explosion of detail is required for a standard assembly this can similarly be broken down and scheduled by the machine.

(3) For the very important overall preparation of detailed main assembly diagrams *etc.*, programmes have been prepared to carry out much of the earlier checking work done by senior draughtsmen. These check programmes can carry out much of the detailed basic checking previously done by hand, since the more junior draughtsman can directly fill in the detailed input form for the computer. Thus, providing the result is satisfactory, he can then present his final drawing and specifications to his senior together with the output from the computer checking programme. This can substantially reduce the amount of time needed for careful checking particularly as the senior will be fully conversant with the checking programme and know exactly what he must check himself and what can be left. Apart from the saving of time the high accuracy of the details prepared by the computer is a valuable extra bonus that is continually being more trusted and appreciated.

Examining Manufacturing Problems

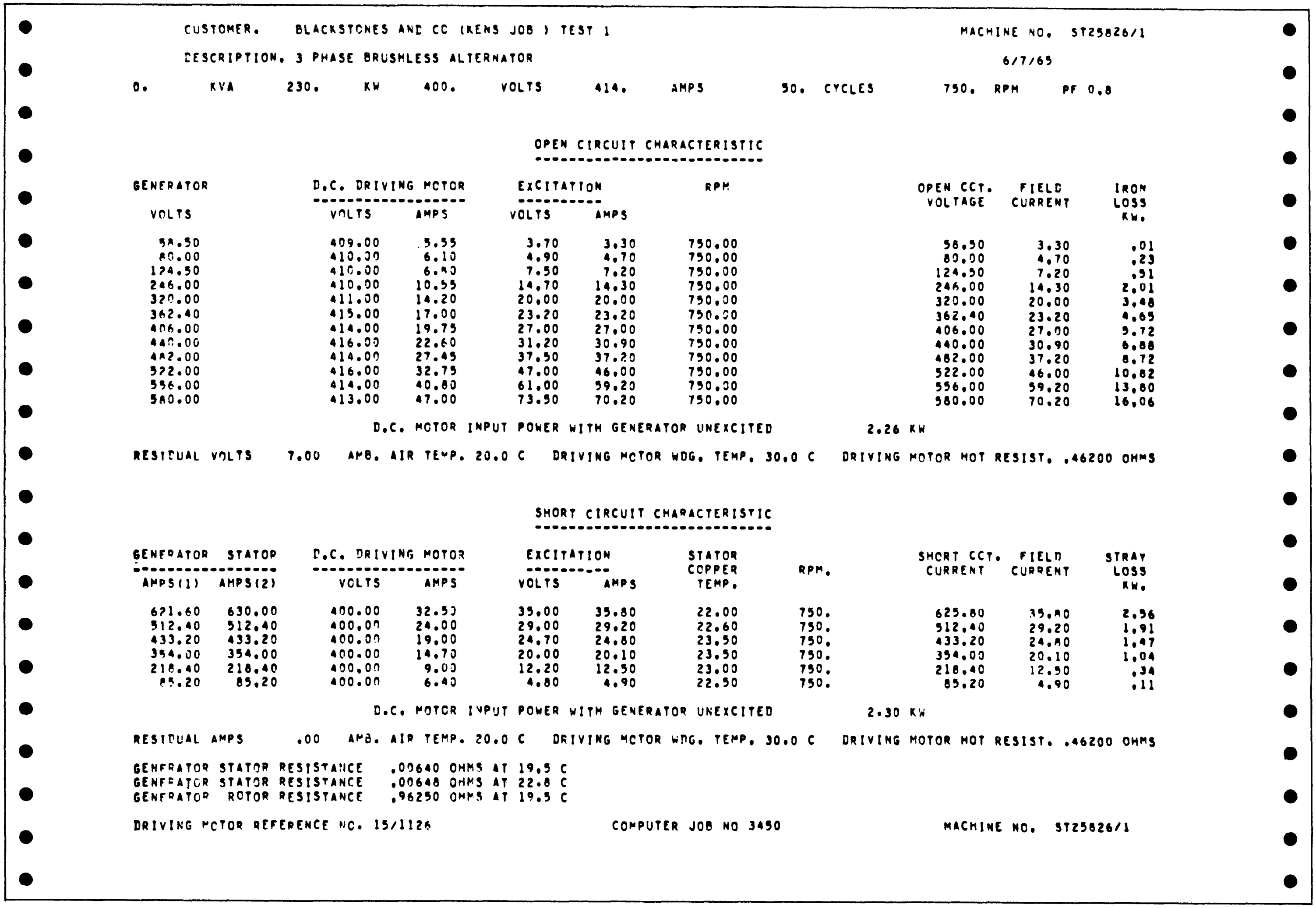
During the course of manufacture, or in test afterwards, there are occasions when the design cannot proceed exactly as originally planned. When this occurs urgent decisions may be called for from the design office and hence the speed at which any modifications can be calculated is most important.

The design analysis programmes, particularly individual detailed items such as mechanical stress programmes, are then heavily used and quite indispensable under these conditions.

Checking Test Results

Because of the pressure of work on design offices, the checking of test results can at times prove a bottleneck. This is naturally a situation to be avoided wherever possible since it directly slows down the flow of work through the production departments. The test calculations required are however often quite complicated; a lot of factors from the basic test figures recorded by the test department (such as the calibration curve of the instruments, the efficiency of the test driving machine for the speed and load, *etc.*) must be properly taken into account in order to derive the exact performance of the new machine under test. This often requires several different types of calculation, including references to various calibration curves, nests of efficiency curves, *etc.* These complications make it impossible to burden the test department with the work and the application of computers to the problem is ideal. Consequently programmes are often prepared which will carry out this analysis and print out the required data both in numerical and graphic form.

Thus work is organized by revising the layout of the test sheets filled in by the test department into a form suitable for direct feeding to the digital computer. The processed results are then returned directly to the test



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        CUSTOMER.    BLACKSTONES AND CC (KENS JOB ) TEST 1                                  MACHINE NO.  ST25826/1

        DESCRIPTION. 3 PHASE BRUSHLESS ALTERNATOR                                                6/7/65

0.         KVA        230.       KW       400.      VOLTS       414.      AMPS         50.  CYCLES        750.  RPM      PF 0.8


                                                    OPEN CIRCUIT CHARACTERISTIC
                                                    ---------------------------

GENERATOR            D.C. DRIVING MOTOR      EXCITATION          RPM                     OPEN CCT.   FIELD       IRON
                     ------------------      ----------                                  VOLTAGE    CURRENT      LOSS
  VOLTS                VOLTS      AMPS     VOLTS     AMPS                                                         KW.

   58.50              409.00      5.55      3.70      3.30     750.00                     58.50       3.30        .01
   80.00              410.00      6.10      4.90      4.70     750.00                     80.00       4.70        .23
  124.50              410.00      6.80      7.50      7.20     750.00                    124.50       7.20        .51
  246.00              410.00     10.55     14.70     14.30     750.00                    246.00      14.30       2.01
  320.00              411.00     14.20     20.00     20.00     750.00                    320.00      20.00       3.48
  362.40              415.00     17.00     23.20     23.20     750.00                    362.40      23.20       4.65
  406.00              414.00     19.75     27.00     27.00     750.00                    406.00      27.00       5.72
  440.00              416.00     22.60     31.20     30.90     750.00                    440.00      30.90       6.88
  482.00              414.00     27.45     37.50     37.20     750.00                    482.00      37.20       8.72
  522.00              416.00     32.75     47.00     46.00     750.00                    522.00      46.00      10.82
  556.00              414.00     40.80     61.00     59.20     750.00                    556.00      59.20      13.80
  580.00              413.00     47.00     73.50     70.20     750.00                    580.00      70.20      16.06

                       D.C. MOTOR INPUT POWER WITH GENERATOR UNEXCITED           2.26 KW

RESIDUAL VOLTS    7.00   AMB. AIR TEMP. 20.0 C   DRIVING MOTOR WDG. TEMP. 30.0 C   DRIVING MOTOR HOT RESIST. .46200 OHMS


                                                    SHORT CIRCUIT CHARACTERISTIC
                                                    ----------------------------

GENERATOR  STATOR    D.C. DRIVING MOTOR      EXCITATION        STATOR                    SHORT CCT.  FIELD       STRAY
-----------------    ------------------      ----------        COPPER      RPM.          CURRENT    CURRENT      LOSS
 AMPS(1)  AMPS(2)       VOLTS     AMPS      VOLTS     AMPS     TEMP.                                             KW.

  621.60   630.00      400.00     32.50     35.00     35.80     22.00      750.          625.80      35.80       2.56
  512.40   512.40      400.00     24.00     29.00     29.20     22.60      750.          512.40      29.20       1.91
  433.20   433.20      400.00     19.00     24.70     24.80     23.50      750.          433.20      24.80       1.47
  354.00   354.00      400.00     14.70     20.00     20.10     23.50      750.          354.00      20.10       1.04
  218.40   218.40      400.00      9.00     12.20     12.50     23.00      750.          218.40      12.50        .34
   85.20    85.20      400.00      6.40      4.80      4.90     22.50      750.           85.20       4.90        .11

                       D.C. MOTOR INPUT POWER WITH GENERATOR UNEXCITED           2.30 KW

RESIDUAL AMPS      .00   AMB. AIR TEMP. 20.0 C   DRIVING MOTOR WDG. TEMP. 30.0 C   DRIVING MOTOR HOT RESIST. .46200 OHMS

GENERATOR STATOR RESISTANCE   .00640 OHMS AT 19.5 C
GENERATOR STATOR RESISTANCE   .00648 OHMS AT 22.8 C
GENERATOR  ROTOR RESISTANCE   .96250 OHMS AT 19.5 C

DRIVING MOTOR REFERENCE NO. 15/1126               COMPUTER JOB NO 3450                 MACHINE NO.  ST25826/1
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Figure 19.4. A typical output result

department within two or three hours of the tests having been completed, and the testers can themselves see whether the results are acceptable to the design office. If they are satisfactory, the results can be passed on to the design office and the machine released for despatch at the same time. Only when the results are clearly unacceptable is there any need to consult the design office and ask for their comments. When this happens, of course, the design office know that there is trouble with the machine and can immediately give it a priority that is impossible to give to a steady stream of ordinary test results that just need routine analysis. A particular programme for the open and short circuit test of a range of synchronous machines carries out the following procedure.

Winding resistance at specified temperatures of the test plant are held, in an easily updateable form, by the computer as permanent data. True voltage, current and resistance values are calculated from the given test figures, instrument constants and temperatures. The various known losses are computed from the above and hence the wire loss and stray loss found. The output will consist of:

(1) Revised input details.
(2) Open circuit curve.
(3) Iron loss curve.
(4) Short circuit curve.
(5) Stray loss curve.

A typical output result is shown in *Figure 19.4.*

General Design Improvement

Accurate and reliable analysis programmes are in continual use in the constant endeavour to improve equipment performance. In the precomputer era, for example, it was only possible to check on the likely improvement resulting from a new material on only a few specific designs; it is now practical and economical to consider quickly a wide range of new materials, dimensions, stress limits, *etc.*, on a range of machines in order to fully ascertain the optimum. The only prerequisite is a clear head by the designer. Usually the number of practical possibilities is small enough to make the need for any logical programming of the survey unnecessary.

Further interesting large-scale application of computers have been in the careful evaluation of all component sizes and ratings in order to construct a complete range of machines from the minimum of stock parts. Further, the programmes carefully space out the incremental steps between sizes to be used in order to optimize on the widest possible range of machines for the lowest overall cost. Thus most of the programmes are highly detailed economic exercises using advanced statistical methods. Not only have surprisingly high savings been achieved but all the variations of range can be tabulated and the breakdown of their parts sorted out at a moment's notice. The programme thus forms an integral part of the stock and production control arrangements for the factory. When necessary the programme is rerun in order to evaluate the cost of revising the optimum designs being produced in the light of trading results and forecasts. Such a programme would be highly complex and need several man years of writing to complete, but could of course quickly pay for itself in a factory which mass-manufactured a standard range of small motors, for example.

Conclusions

In my experience, computers have proved most beneficial where they have been used as aids to designers, and not as substitutes. The reasons for this are described for the specific case of electrical machine design by CONCEICAD and PARTON (1963), and the subject is discussed fully by PARTON (1964). The broad issue however is that design is basically an art more that a science, and although computers can be programmed to prepare regularly an adequate design quite automatically, this design will hardly ever be the best.

It is this little bit extra that the human designer's intuition and experience can contribute that is vital in modern markets and must always be encouraged. The role of the computer must be to take over as much as possible of the routine aspects of design in order to leave designers free to concentrate their abilities on the fundamental design, work where the computer is very much inferior.

Acknowledgments

I would like to thank the General Electric Company Limited for permission to publish this chapter.

Chapter 20

A PRACTICAL DESIGN: AN OIL BURNER FOR LARGE WATERTUBE BOILERS

A.M. Needham

Introduction

This chapter concerns the practical design of a critical component for an existing plant which had to operate on a different fuel from that originally specified. It shows the need to study the interrelationship between the components of the system and how the analysis of the effects resulting from the change of fuel, together with an analysis of the system operation, enabled an outline specification for the component to be defined. From this specification, a design was developed on the basis of existing knowledge, employing rig testing where it was not possible to predict performance. The selection of materials and the detail design of the component were based on ensuring operational reliability under all phases of the system operation.

As a result of these studies, together with personal knowledge of plant conditions, the new component design has fulfilled expectations completely.

Plant

A number of Central Electricity Generating Board Power Stations were converted from coal firing to oil firing in the late 1950's. These power stations were mainly coastal stations with adequate berthing facilities for the tankers delivering the heavy fuel oil from various oil refineries. Many problems were encountered resulting from burning heavy fuel oil in boilers originally designed for burning coal, and not all have been successfully solved. The major outstanding problem is the corrosion of various parts of the boiler system which is caused by burning fuel oils with a high sulphur content. When these fuel oils are burnt sulphur dioxide is formed, and a small percentage of this is further oxidized to sulphur trioxide. This condenses in the cold parts of the boiler, notably in the air heater and combines with the water vapour present in the flue gases to form sulphuric acid.

The quantity of sulphur trioxide formed can be limited by reducing the amount of oxygen available in the combustion zone and considerable success has been achieved by this method. However, it has been shown by several laboratory investigations and a few boiler operations in Germany that the excess oxygen in the combustion zone must not be more than 0.2 per cent greater than the stoichiometric system requirement for complete elimination of sulphur trioxide. This corresponds to a quantity of 1 per cent air in excess of the stoichiometric or theoretical amount required to burn the fuel completely.

The Problem

The boilers at a typical power station (*Figure 20.1*) could not be operated at this very low value of excess air because carbon monoxide and smoke were produced resulting in a drop in boiler efficiency and infringement of the Clean Air Act. Also the final steam temperature was reduced because of the change in the heat transfer within the boiler.

One burner was tested on a combustion test rig and it was found that smoke was produced at an excess air level of 5 per cent and that it was not possible to obtain the required air flow through the burner itself when operating at the normal fuel flow. Even at the maximum air pressure which could be obtained on the boiler there was insufficient air flow through the oil burner to achieve the stoichiometric air–fuel ratio. It was found that the boiler was operated at above stoichiometric air–fuel ratio only because of inleakage of air either through the boiler casing, or through the small burners used at start-up only.

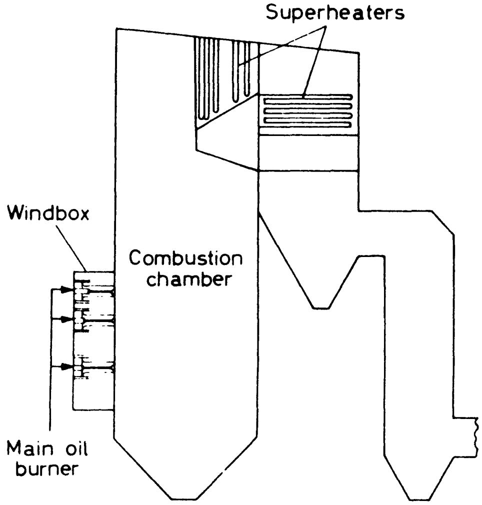


Figure 20.1. Boiler plant

As a result of these tests a decision had to be made on whether to try to develop the existing burner or to design and develop a complete new burner. The power station staff were consulted and decided to adopt the latter course. This decision was influenced by a number of factors both practical and theoretical.

Boiler Operation

A study of the operational records of the boiler and turbine showed that the normal output was 58–60 MW with infrequent continuous loads of 40 MW and occasional peaks of emergency generation of 66 MW. The boiler and turbine had been designed for maximum efficiency at an output of 60 MW. The variation in steam output only varied from 66 per cent to 110 per cent of the normal load.

The burner fuel system had been designed to have a 10 : 1 variation in fuel flow and to give a good fuel atomization over this range a spill system of atomization was used. Twelve oil burners had been installed on the boiler and variations in output of the boiler were achieved by altering the fuel flow to all of them. The air supply was also common to each and could be adjusted in proportion to the fuel flow. As the maximum air pressure possible was 6 in.w.g., and since flow is proportional to the square root of the pressure, the windbox pressure at 10 per cent fuel flow would have to be 0.06 in. w.g., that is 1/100th of the full pressure. Obviously, this could not be achieved in practice and the minimum windbox pressure which could be used was 1.5 in.w.g. Below this pressure combustion would become too poor for normal boiler operation. The variation in boiler output was 2·1, fixed by the air flow and not the fuel flow.

It was therefore decided to dispense with the spill system of oil atomization and use simpler pressure jet atomizers, thus reducing the number of valves on the fuel system by half. Boiler output could be controlled in steps of 5 MW by shutting off burners, and in stages of less than 5 MW by adjusting the fuel pressure. The variation in output required on each burner would then only be down to 87½ per cent of full load, taking the case of a 40 MW load with eight burners in operation. The corresponding change in fuel and air pressure would be down to 72 per cent of the maximum.

Superheat

The steam supplied from the boiler to the turbine must be at a constant temperature at all loads as the efficiency of the turbine is very sensitive to changes in steam temperature.

It has been found on all oil fired boilers that as the load decreases the final steam temperature falls and the boiler has to be operated with higher excess air to maintain steam temperature.

It was reasoned that this is because the flame shape and total radiation change little as the air velocity is reduced. To maintain a constant final steam temperature at a constant air–fuel ratio, the ratio of the heat transferred by radiation to that transferred by convection must be approximately constant. However, flame size and emissivity is a reciprocal function of air velocity, since this governs the rate of mixing of fuel and air.

Observations made at normal and reduced load conditions with the original burners showed that there was little change in the total flame envelope. This would indicate that the amount of heat radiated from the flames did not change significantly as load was reduced and thus less heat was available for transfer to the steam by convection in the superheater.

If the system of shutting off burners to reduce load and operating the other burners under nearly constant conditions were adopted, the total flame envelope would be reduced proportionally to the load. It appeared hopeful that the amount of heat radiated would be reduced, enabling final steam temperature to be maintained at all loads at a constant air–fuel ratio.

Burner Design

Once the broad requirements of the burners necessary for improved operation of the boiler were decided, the more detailed design requirements could be listed.

Air Nozzle

The air nozzle diameter fixes the velocity of the air through the burner for a given fuel flow and given air–fuel ratio.

It was known that for good combustion, a velocity of the order of 100-200 ft./sec, would be required and so a diameter was fixed to give a velocity of 150 ft./sec under normal fuel flow conditions. The final size could only be determined after testing the burner under simulated contitions.

Stabilizer

The stabilizer provides a stable recirculating zone of fuel and air local to the atomizer. When this zone is ignited it provides an ignition source for the remaining fuel–air mixture. A swirl vane type of stabilizer which had been previously developed for a smaller oil burner was known to be effective and so this was scaled up to suit the larger air nozzle, the ratio of the cross-sectional areas being made similar.

The air nozzle and stabilizer size govern the flame length and combustion performance to a large extent. The maximum flame length which could be tolerated was fixed by the dimensions of the boiler, and as there was no method of predicting burner performance, rig testing and development were necessary to ensure that the oil burner would be satisfactory when installed on the boiler. This development work was entirely confined to the air nozzle and stabilizer and so the other burner parts could be designed to meet the specification implied by the operational requirements.

Atomizer

An atomizer size was chosen which gave the required fuel flow at the normal fuel pressure used on the boiler. The spray angle has an important effect on combustion performance and the most suitable angle would be determined during the rig testing of the oil burner. However, the external size of the atomizers of different spray angles are the same and so whichever one was finally selected, the mechanical design of the burner would not be affected.

Air Valve

The air valve or register directs the air from the windbox into the air nozzle. The air is accelerated from a low velocity and is also turned through 90°; this should be done with the minimum loss in total energy as losses at this point serve no useful purpose. The only pressure loss which is necessary is that caused by the stabilizer in creating the recirculation zone for flame stability.

The air valve was therefore designed aerodynamically, and based on the principles used in the intakes for static testing of jet engines where similar flow conditions apply. The pressure loss was expected to be less than 6 per cent of the total energy.

The overall pressure drop of the burner would be mainly determined by the air nozzle area and the stabilizer blockage. Calculations based on the sizes initially selected and an estimated blockage for the stabilizer showed that the quantity of air required for stoichiometric air–fuel ratio at the normal fuel flow would pass through the burner at a windbox pressure of 3 in.w.g. Examination of the forced draught fan and the system pressure loss characteristics showed that at this windbox pressure the required air flow could be obtained at 75 per cent of full fan speed. Air control on this boiler was regulated by means of fan speed and so fan power required would be less with the new burners.

Sealing

As the boiler was to be controlled by shutting off burners to reduce boiler output it was essential to design the burners so that, when they were shut, all air would be sealed off from the windbox. If this was not done then, since the boiler was to be controlled to a low overall excess air rate, the burners which were firing would be starved of air; the air leaking through shut off burners would provide the required amount. This would affect the flame shape and emissivity of the burners firing and final steam temperatures would fall, making it necessary to increase the excess air rate to maintain final steam temperature. Thus the whole effect of modifying the oil burners to give low excess air rates at all loads would be lost.

Materials

The burners which are shut off have no cooling air passing through them and so the air nozzle, stabilizer and atomizer soon reach very high temperatures. The gases in the combustion chamber contain products of vanadium and sulphur which can reach these burner parts when the burner is shut.

The best material for these conditions was known to be a high chrome low nickel steel, to AISI 309 specification, and so the stabilizer and air nozzle were designed to be made from this material. The atomizer was made from a hard stainless steel which softens with excess heating, resulting in rapid wear. This part thus required protecting from heat and so was designed to retract inside the air nozzle, together with the stabilizer, when the burner was shut. This would shield it from direct radiation from the flames of the other burners.

A further point which had to be considered was that, although the oil pipe and atomizer are purged of oil when the burner is shut down, some oil remains inside. When this is heated excessively, cracking of the oil takes place, leaving hard carbon deposits which can block the small orifices of the atomizer. A passage was therefore designed so that cold air from the boiler house would be drawn down the tube supporting the oil pipe and atomizer. A radiation shield in front of the atomizer was also designed to direct this air over the atomizer face. Cool air would always be drawn down the tube because of the low pressure zone downstream of the stabilizer when the burner was operating. When the burner was shut off, air would be drawn in since the combustion chamber is operated at below ambient pressure for safety reasons.

Air Distribution

In any type of boiler installation with a number of burners taking air from a common duct or windbox, there is usually a maldistribution of air to each burner caused by static pressure variations both in the windbox and in the combustion chamber. Thus it is desirable to be able to adjust the air flow on each burner, and if a boiler is to be operated at nearly stoichiometric overall air–fuel ratio it is essential. Otherwise, some burners will operate with high excess air rates and the others with a deficiency of air, resulting in the former producing corrosive SO_3 and the latter producing carbon and possibly smoke.

The adjustment of the air flow should not affect the flow pattern through the air nozzle, otherwise combustion performance would be altered. The obvious way of achieving this was to alter the amount by which the air valve could open.

Detail Design

The basic framework of ideas for the oil burner were now formulated and detail design of the hardware was commenced *(Figure 20.2).*

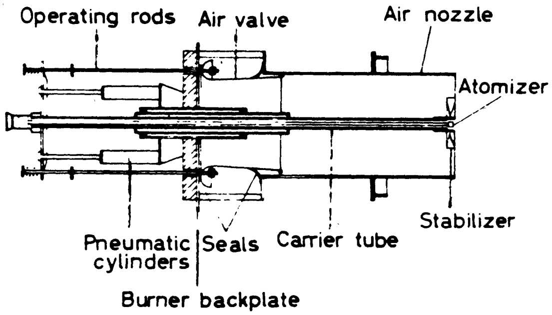


Figure 20.2. Oil burner

Sizes of certain parts were fixed by the dimensions of the existing windbox and so the outline of the complete burner was laid out.

At the same time a very simple burner was drawn and manufactured for testing on the combustion rig. This was simply a fixed air valve and nozzle combination, which could be easily changed, and a central tube carrying the stabilizer and atomizer. A number of different size air nozzles and stabilizers were manufactured to enable the tests to be carried out in the minimum time.

It was anticipated that the air nozzle diameter would not vary as a result of combustion tests, by more than ± 2 in. from the diameter estimated, so making it possible to finish the detail design before complete test results were available.

A number of important factors were considered when designing:

(1) Ease of maintenance,
(2) Expected life,
(3) Weight,
(4) Method of manufacture,
(5) Cost.

If the loads which could be expected in the normal operation of the burner were considered alone, the whole burner could be manufactured in 16 s.w.g. materials. However, the air nozzle could be subject to corrosion and high thermal stresses and, aiming at a minimum life of 3 years, it was decided to increase the gauge of this part. Consequently, the rest of the burner had to be strengthened not just to carry the loads but to allow for the type of handling which the burner would receive when being fitted to the boiler.

To reduce maintenance to the minimum, simplicity of design was aimed at, with the least possible number of moving parts. The pneumatic cylinders necessary to actuate the retracting of the stabilizer and atomizer were also used to operate the air valve. In order to reduce their working temperature, these cylinders were mounted as far as possible away from the burner backplate.

The igniter, a propane gas–electric torch, was fitted just above the tube carrying the stabilizer and a larger tube carried both through the two supporting bearings. This design eliminated a separate mounting for the gas torch and its actuator.

Since only twelve burners were required and because short delivery was essential, it was decided that it would be cheaper to use fabricated parts. With this in mind, all efforts were made to reduce costs by making parts from stock sizes of material where possible.

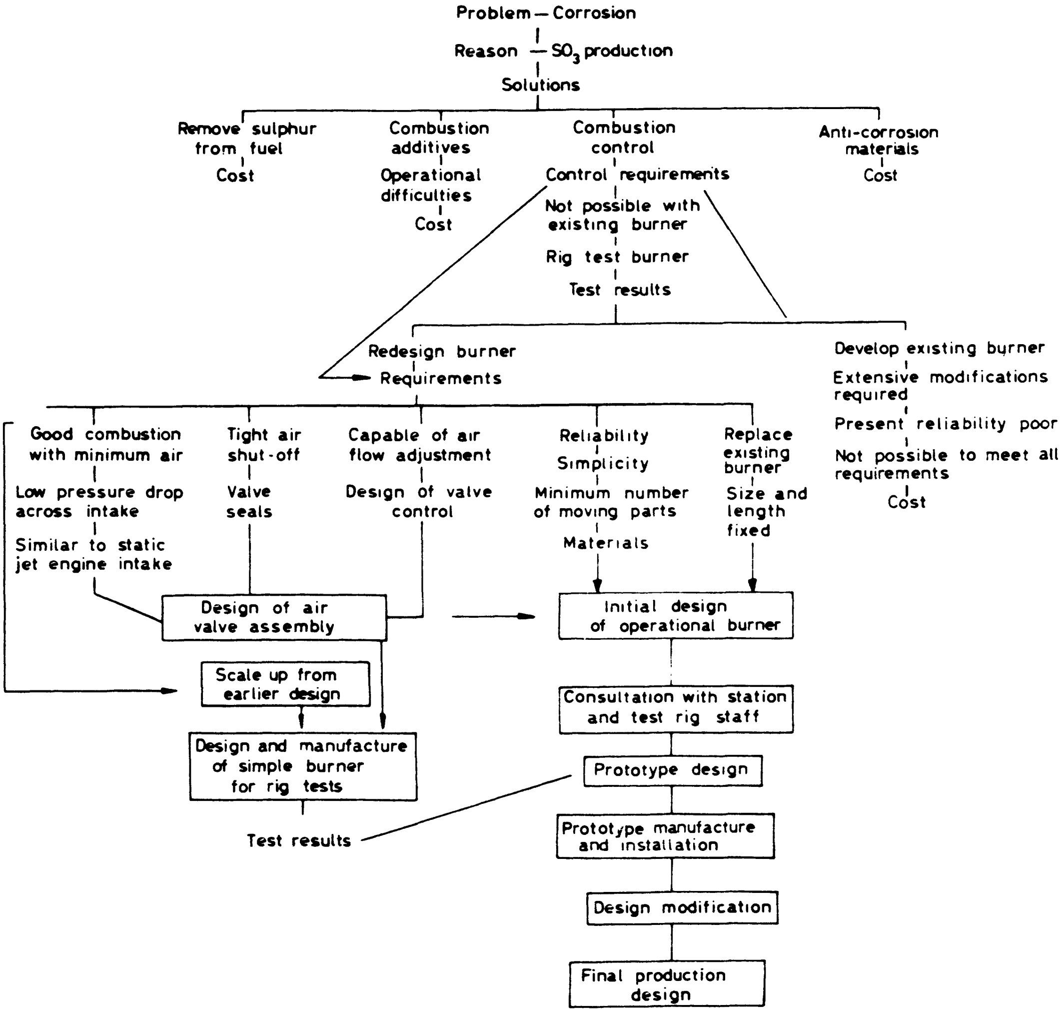


Figure 20.3. The application of information in the design process

Stock lists of local suppliers were found to be far more useful than reference to British Standards to obtain tube sizes. Also, since it was known that the larger diameter rings would be cut from stock size sheets, the external diameters were made so that two rings could be cut from one sheet, thus reducing wastage.

Prototype Burner

The results of the rig combustion tests showed that the size of air nozzle and stabilizer first estimated were the most suitable for the boilers. This was fortunate and enabled a prototype burner, for installation on the boiler, to be manufactured and tested before converting all the burners.

The manufacture and installation were personally supervised by myself and a number of changes in the design became obvious. Because of the wide tolerances which had originally been allowed, it was necessary to increase the clearances on parts which had to mate with existing fittings on the boiler. These modifications were incorporated in the design of the production burners.

Boiler Conversion

Following the successful three month trial of the prototype burner, the other eleven burners were similarly modified and installed. On recommissioning the boiler, no difficulties were experienced with the operation of the burners. The boiler performance came up to the expected standard, and superheat temperatures could be achieved easily at part load. The control of the boiler during start-up also improved, because of the elimination of inleakage air through the burners not in use. However, the improvement of the oil burners has shown up the poor sealing of the boiler casing. Although the burners are operating at nearly stoichiometric air–fuel ratio, the overall excess air rate is still too high to prevent the formation of sulphur trioxide. This excess air must be entering the combustion chamber through the boiler casing, since special attention was paid to the small burners used for start-up during the overhaul period and these appear to seal well when shut. The inleakage has increased since the boiler was recommissioned following replacement of some boiler tubes and is much worse than was originally expected. Steps are now in hand to improve the casing and so bring the excess air under complete control.

Conclusions

This case history of the design of an oil burner is intended to show the need to consider not only the part being designed but its interrelationship with other parts. First-hand knowledge of the operation of the plant, as well as adequate consultation with the plant engineers and operators, enabled a satisfactory design outline to be formulated. Close association with the combustion test rig team resulted in many possible difficulties of burner operation being eliminated in the design stage. The personal supervision of the installation, as well as discussions with maintenance staff, greatly influenced the detail design of the burner.

A flow diagram which indicated how all this information was used in the design process is shown in *Figure 20.3*. This illustrates how complex the design of a relatively simple component can be and the important part that good communications play in the design process.

I believe that a designer must be not only a person who can produce elegant designs but also one capable of explaining designs to the people who will use them, and of obtaining their co-operation and experience to assist him in producing the best design to meet the requirements at the least cost.

Acknowledgment

I wish to thank Mr. R.H. Coates, Regional Director of the South Western Region of the Central Electricity Generating Board, for permission to publish this chapter.

Chapter 21

PRACTICAL DESIGN BASED ON METHOD (FUNDAMENTAL DESIGN METHOD)

E. Matchett and A.H. Briggs

Introduction

This chapter has three primary objectives:

(1) To introduce a method of developing further the design skills possessed by senior practising designers, laying particular emphasis on the kind of learning environment which has been created for this purpose.

(2) To outline some of the kinds of thought and feelings that a designer experiences during this development process in which formalized design projects are integrated with more traditional methods of designing.

(3) To invite discussion on possible weaknesses in such learning processes and how they might be overcome, and on how their strengths might be further exploited – both in connection with designers of considerable experience, and those just entering the profession, whose level of skill will influence tremendously the pattern and quality of future civilization.

Many of the remarks made are illustrated by a practical example studied on the Fundamental Design Method Course at Engineers' House, Bristol. Though this example is reproduced in some detail it has not been possible to cover all aspects of the study, as this would have required far too lengthy and tedious an exposition. It should also be noted in connection with this example that it employs only that part of the formal design approach covered on the course which appeared best suited to the needs of the particular design project and of the particular individual concerned. Much of the method content of fundamental design method lies at a deeper level than the application of a systematic approach analogous to a computer programme, in that it intimately involves a major part of the designer's total mental skills, attitudes, knowledge and personality. There is little similarity with the kind of method that is a mere manipulation of formulae.

The Fundamental Design Method Course

The course is based on the concept that the extent to which a designer is able to improve further his design ability, is closely allied to the extent to which he can become aware of his mental skills and attitudes employed in designing.

The emphasis in all of the course work is on the further development of the individual's mental skills and on how the individual can make better use of existing and future knowledge in the designs of his company's products. In order to achieve this it is necessary for each course member to reflect deeply upon the methods and objectives embodied in his daily work, particularly within that part of the work which is the most creative and important. It is assumed that within this part of his work there are inadequacies and redundancies of thought of which he is unaware, yet which will open up possibilities for improved design once they are discovered.

The course is intended for senior practising designers holding positions of responsibility. Each individual designer is expected to explore, under guidance, his own mental skills and attitudes and determine for himself how he might more fully exploit their strengths and remedy their weaknesses, and work more deliberately and thoroughly towards clearly defined and carefully analysed objectives.

As a result of the course, and the subsequent train of events it is calculated to produce, a designer should obtain a progressively increasing degree of conscious control and systematic working, with a heightened awareness of what mental actions are necessary at any point in the design process.

Each course member is visited before the course to ensure that, as far as is practicable, the tuition he will receive will suit his own and his company's needs. A design project is selected which is typical in scope and complexity of the work which forms his most difficult assignments. The choice is usually difficult owing to the very short period of time allocated to the project on the course, and the desirability that a satisfactory solution be found during the three-week course. The visit also serves to prepare the designer for the kind of experience he is to undergo and to motivate and condition his thinking, so that maximum benefit may be derived from the course tuition and practical work. Lack of preparation prior to the course and lack of factual data would require assumptions to be made on the project; this would then become more of an academic exercise than a determination of how to satisfy the demands of a real and exacting set of circumstances.

The course is residential and assignments are arranged for every evening and for the first and second week-ends. This provides a means of employing fully what is admittedly an extremely short period of time in which to help bring about significant changes in a designer's capabilities. The results of all the projects tackled and other practical work, are exhibited on a course Open Day to which members of the companies represented are invited. This acts as an added incentive for achievement and provides a deadline which adds reality to the exercise. The opportunity to describe and discuss the methods and results helps to consolidate what has been learnt.

The tempo of the course is as rapid as possible, consistent with the achievement of an adequate depth of thought. Apart from lectures, group discussions, and the individual project, each course member takes part in several exercises and group projects, being responsible for one of the latter as a group leader. Care is taken to arrange the groups so that each man is likely to benefit from working with particular individuals.

The bulk of the formal tuition is concerned with building up model concepts of the design process and objectives, which become basic standards, used to direct and evaluate subsequent design thought. This involves the study of skills and attitudes which all successful designers probably possess to a considerable degree, though usually without realizing either their presence or their importance. Particular attention is given to describing the most fundamental and most commonly used elements of design thoughts which, to date, it has been possible to identify. The course member is not invited to accept such descriptions but rather to grapple with them, try to discover flaws in them, and make them personally more meaningful. Once this is done, however, he is expected to attempt to make use of the knowledge in all his design work. The revised model concepts become the yardstick by which he decides whether the thoughts with which he is currently occupied are timely and in line with what is theoretically required. In effect he uses mental signposts and landmarks which he himself erected during the process described above.

It is very important in this kind of training that the course member absorbs and digests material given in lectures, so that it becomes second nature to apply it at speed. Unless the bulk of material is so digested through thought and practice during the course, it is unlikely that the intended improvements in mental skills will be acquired as a result of reading course notes afterwards. This remark would also apply to a great number of methods of charting and analysing thoughts, which are discussed during the course. The solving of any problem is aided by the fundamental basis underlying all such methods, rather than by attempts to employ a rigid technique.

To cover the ground in depth is not possible without the whole-hearted co-operation of each individual. Much of the material which repays the deepest study is superficially simple and obvious, yet it is essential that from the outset one is prepared to grapple with this. Other vital aspects of one's thought processes involve factors which are not readily identified in lectures, *etc.*, and which must be approached by use of analogy. For example, physical activities and methods of analysing these, present a useful analogy to mental actions and their analysis, provided that a person is prepared to make use of such aids to understanding. Significant progress on the course is not possible without such endeavour. Each individual is required to consider objectively aspects of his own thinking which may not be similar to that of other people. He can only be assisted up to a certain point, beyond which a concentration of thought and energy is required that can only be his own.

Several of the course exercises are concerned with simply writing reports on what one believes to be the stages, and criteria of judgment, employed in reaching design decisions of different kinds. The early exercises are almost entirely unstructured, but later ones invite comments on specific aspects concerned with the application of the imagination and judgment, and particular difficulties one is likely to experience. Such exercises are not easy to construct in that they must, with as little biasing effect as possible, draw out from the individual those details of the approach he has been using which can be most beneficial to him once they are exposed. This is normally not at all easy to achieve and the fact that the course members do persevere in trying to do so, even though the process involves a good deal of strain, is indicative of the interest such a form of study generates.

It is sometimes suggested that this kind of learning places a person under too much strain and makes him too susceptible to suggestion. It is true that the course is designed to change people – the development of one's abilities is not possible with a change occurring. Although there is good evidence to suggest that change does take place, and often appreciable change, there has been none to date to suggest any sign of change for the worse. People's skills are developed, their horizons are widened and they obtain greater satisfaction from the deeper insight into, and control over, their work. There is frequently evidence of a new dignity and enthusiasm which emerges from knowing more about the tremendous achievement that any design work of quality represents – whatever the current status of a designer in the eyes of the world.

An Example of the Application of Fundamental Design Method

The project arose out of the need for the company concerned (English Steel Corporation Limited, Sheffield) for a mine car coupling

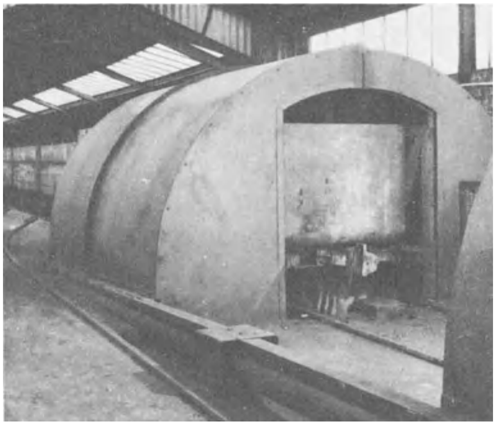


Figure 21.1. Typical tippler installation

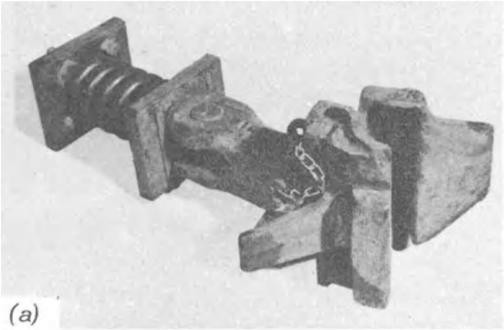
which would dispense with manual operation at the uncoupling and coupling stages. Such operations had become a standard practice in many coal mines, where the mine cars are discharged by rotary dumping which necessitates temporary separation of the train (see *Figure 21.1*).

The Willison mine car coupler couples automatically but must be uncoupled manually, and in some cases must be neutralized so that the cars may be shunted together without coupling. Previous methods of neutralizing Willison couplers are shown in *Figure 21.2*. Reports were received from the service engineers which made it obvious that as coal production increased, haulage efficiency must also increase to keep pace; one way of doing this would be to produce a fully automatic coupler which dispensed with the need for manual operation, and thereby from the customer's point of view reduced manpower.

The project was chosen for the Fundamental Design Method Course, where the major features of the new design were established. Calculations, detail drawings and subsequent prototypes have proved the effectiveness of the design which is shortly to be manufactured in large quantities.

As with all projects studied on the course, an attempt was made to record those parts of the design decision process, and relevant factors, which were judged to be most likely to justify detailed study.

Such a judgment is largely a matter of employing one's past experience, though this proved far less valuable in the early stages than the idealized model concepts of the design process and fundamental elements referred to previously. In order to expose the decisions involved, a number of charts based on those given on the course, but modified to suit the particular project, were drawn. It should be noted that these charts to some extent took the place of sketches which would normally have been produced in such a design study. They also recorded thoughts which would



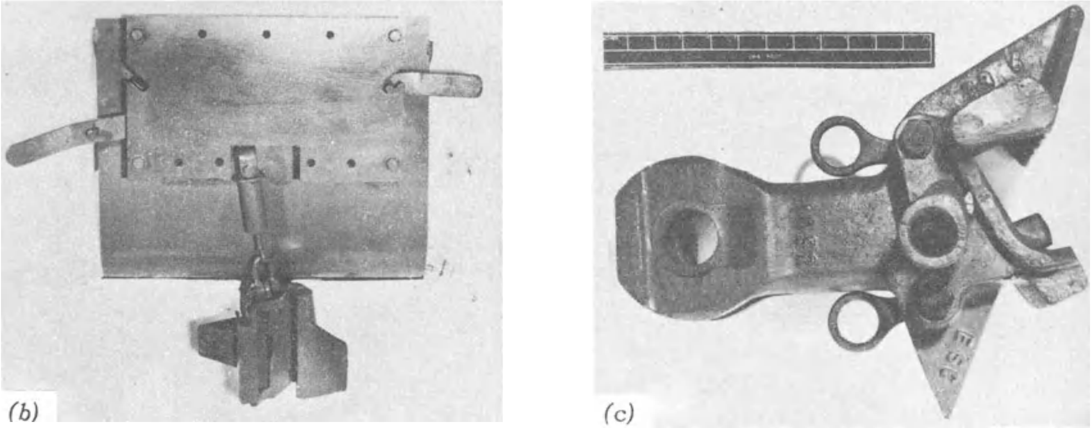


Figure 21.2. Previous methods of neutralizing Willison couplers: (a) coupler with lock retraction pin; (b) coupler with operating gear on car end; (c) integral coupler with neutralizing plunger

traditionally be the non-recorded links between sketches. Such normally non-recorded thoughts and factors include the reasons for making a decision, reasons for deciding against a particular course of action, relationships of items in time and sequence, the number of factors influencing a particular characteristic, and the patterns and trends of decision clusters. The value of formally recording such thoughts and factors can be judged from a detailed study of the full series of charts (*Figures 21.3* to *21.12)* produced whilst evolving the design. One should particularly observe in this connection an additional benefit of using charts in preference to sketches in the early stages: this is the greater freedom from the biasing and restricting effect of anything pictorially defined. Its pictorial form almost inevitably triggers off only such ideas as are closely allied to it.

The particular series of charting methods chosen proved to be a useful one. Initially, the ones shown in *Figure 21.3* to *21.5* were most helpful towards obtaining a rapid feel for the problems involved, and for the most likely area in which a practical solution would occur. Once this was sufficiently determined a sketch design was produced to act as a catalyst for further charting. Every subsequent chart was produced as a result of a deficiency in the preceding one, which concentrated thought around it had revealed. This progression of the charts is important, and is closely interrelated with the striving for some decisive clue as to which path to take. Hence both the nature and sequence of charting are not a matter of simple logic which can easily be explained and copied for other projects, but arise out of the needs of the project in hand and the needs of the individual concerned. The lead obtained on how to proceed is probably more related to the intensity and concentration of the individual's own thinking than his detailed knowledge of charting methods available, or the clarity of his concepts of design fundamentals.

Related to this last comment is another vitally important one. Although the charts are produced individually and are initially analysed in that sequence felt to be sensible, the intensity of thought involved is such that the salient points of all previous charts tend to be kept in mind when analysing any one of them. There is a frequent back-checking of the significance of a proposed decision or new factor revealed. The fact that all previous decisions and data have been recorded is of immense value in rapid thorough cross-checking. This value is, however, minor compared with the effect that the initial exposure of thoughts has had in bringing them and their various relationships into the centre of one's mental focus.

Another important general point arising is that the mental breakthrough which has been sought by means of the charts frequently appears to have no connection with them on superficial examination. It might appear to be a new factor or aspect not recorded on the charts, but is actually a projection of the recorded factors and aspects which has been created by concentrated thinking around the information charted. One does not know what one is looking for until it appears, yet it appears because one has been looking for it and it is readily recognized as a solution.

For those who would object that such an approach is neither scientific nor very systematic, we would be only too happy to agree. We would point out, however, that it works, and works well. What is actually happening is that 'human computers' are being given at least more positive guidance than before, whilst being freed from much bias often found in designing. It is an approach which permits a good deal of systematic design without having to resort to the use of electronic computers. It is also one which is highly practicable until such a time as the design process is so understood that satisfactory computer programmes can be written. The design considered, though relatively simple, involves many thousands of factors and their interrelationships. No method is yet known which is capable of producing the design by computer (certainly not in the thirty hours actually taken to produce this design); neither is any design method so systematic yet so simple as to dispense with the need for the concentration of thought applied to this project.

Major Phases in the Design Study

(1) Investigation of primary functional need – the one need which if not satisfied invalidates all other achievement (see *Figures 21.3, 21.4* and *21.5*).

(2) Design sketches to provide partial or complete solutions to the primary functional need (*Figure 21.6*).

(3) Preparation of a list of items and the functional means they provide (*Figure 21.7*).

(4) Study of the possibility of eliminating, combining or transferring *etc.*, items or whole sections of design (*Figure 21.8*).

(5) Use of the functional process chart to show the sequence of operation of design (*Figure 21.9*).

(6) Charting of operational variations of coupling and uncoupling devices (*Figure 21.10*).

(7) Use of the functional process chart for new design (*Figure 21.11*).

(8) Study of motion of operating cams (*Figure 21.13*).

(9) Preparation of wooden models to check operation of 90° and 180° cam mechanisms (*Figure 21.14*).

(10) Preparation of preliminary sketches of parts of mechanism and preliminary stress calculations.

(11) Preparation of prototype coupler including modifications to parts to ensure correct form of operation (*Figures 21.15, 21.16* and *21.17*).

(12) Preparation of final drawings and detail stressing (*Figure 21.18*).

(13) Use of chart to check functional effectiveness of the design (*Figure 21.19*).

(14) Investigation of field application (*Figure 21.20*).

(15) Histogram prepared to show relative usefulness of each scheme as an aid to implementation (*Figure 21.21*).

(16) Release of designs for trial production (*Figure 21.22*).

Detailed Description of Charting and Analysis on the Project

The design process was commenced by drawing up a chart of the primary functional needs of the proposed design (*Figures 21.3, 21.4* and *21.5*). Although not shown on any of the charts, one of the primary functional needs of the company was that the device must be contained within the head of the coupler, and that the coupling contour was not to be modified because of the necessity of interchangeability with existing couplings. The primary functional need chart listed the various basic methods of operating a coupler. After consideration it became apparent that only a mechanical device could be used on the coupler, although a hydraulic or mechanical means, or combination of both, could be used to operate the track device. It was later established that a mechanical track device would give the simplest solution.

To initiate the thought process, a sketch was made of an extremely inelegant device which nevertheless satisfied every aspect of the primary functional needs (*Figure 21.6*). In this sketch, the finger *A* makes contact with the neutralizing stop on the track device and is rotated through approximately 70°. The spindle *B* and peg *F* also rotate against the spring *I* in torsion and the collar *G* is raised against the spring until the peg *F* positions itself in the V-notch. As the finger *A* rotates the double cam *C* inside the coupler also moves through the same angle and retracts the lock *D* against the lock spring *E*. (The lock and lock spring are not illustrated.) To reset the mechanism, a ramp in the centre of the track raises the plunger *H* which in turn lifts the collar via the connecting pin *J*, thereby releasing the peg *F* which permits the spring to

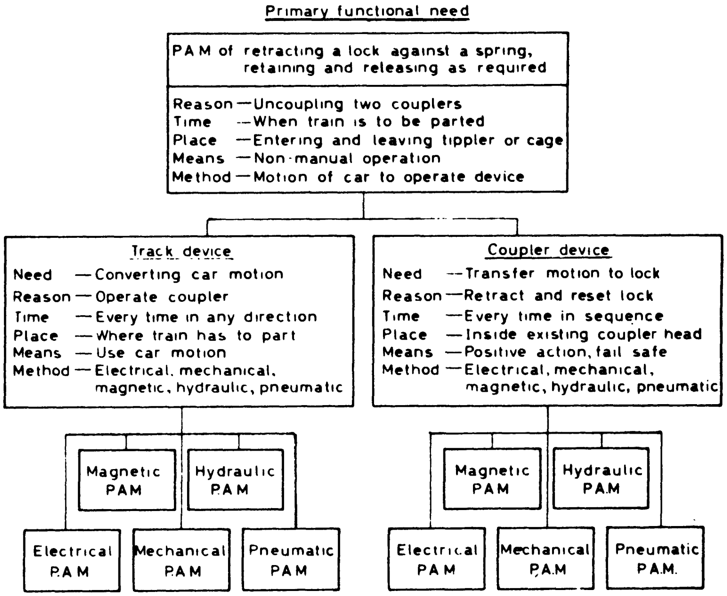


Figure 21.3. Investigation of primary functional need

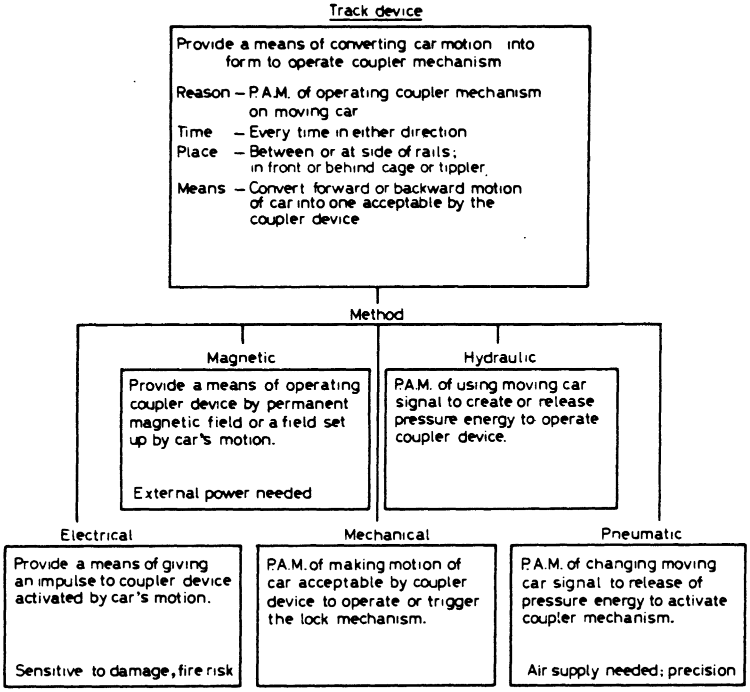


Figure 21.4. Investigation of primary functional need of a track device

return the spindle *B* and finger *A* to their original positions. In doing so the lock is returned to the reset position by the lock spring as the cam rotates to its original position.

This mechanism could operate in both directions of travel by the use of two lock stops, (one on each side of the track centre line) and two ramps (one in front and one behind the lock set stops.) However, it would be essential that the leading ramp be lowered into the track so that the lock set stops operating first. Some method of sensing by the motion of the cars would be required to present the ramps in the correct sequence.

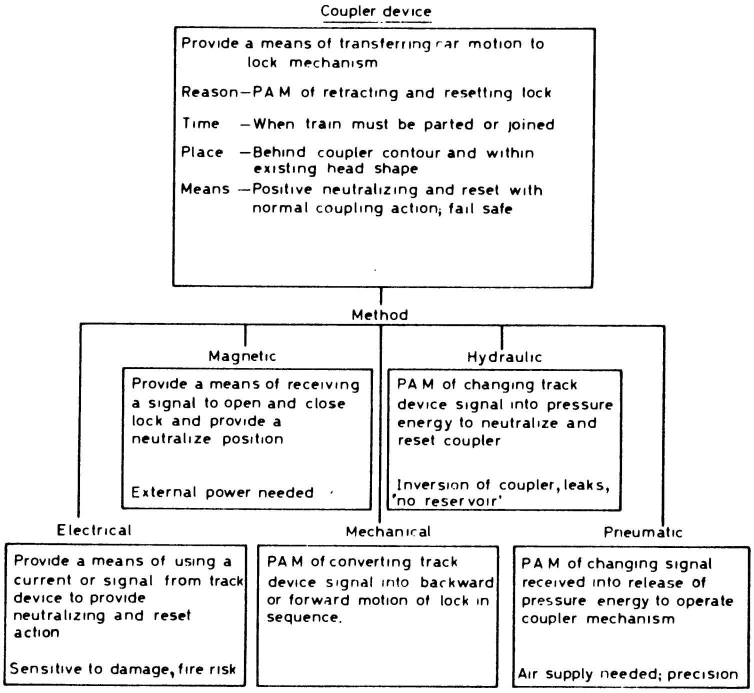


Figure 21.5. Investigation of primary functional need of a coupler device

The next step in the process was to list the parts of the mechanism and against these record the functions which each part carried out (*Figure 21.7*). From this it became evident that certain parts of the tentative proposal were of minor importance while others were carrying out several essential functions. Possibilities for combinations of minor items became apparent but no revolutionary changes suggested themselves immediately.

Then it was decided that a different kind of charting would be necessary to produce the required breakthrough. Each part of the mechanism was listed as in *Figure 21.8* and compared with every other part in turn to ascertain all possibilities of elimination, combination, transference or standardization.

This chart emphasized what had become apparent in the first, namely that certain areas of the mechanism were likely to contain major redundancies, although the precise location of these redundancies was not clear. It was concluded that the key to the solution probably lay in a fundamental dimension not exposed on either of these charts, possibly the time dimension. (Fundamental dimensions available comprise need, reason, time, place, means and method.)

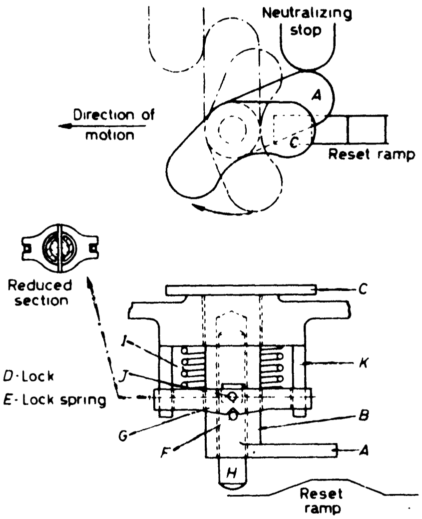


Figure 21.6. Design sketch of a partial solution to the primary functional need

A functional process chart (*Figure 21.9*) was produced to reveal the sequence of operation of the various parts of the coupler mechanism during the neutralizing and reset operation. This chart to some extent indicates areas or items having unnecessary or non-useful motion.

Functional means provided

Coupler
PA.M. of retracting and holding lock non-manually in sequence

Lock
PA.M. of Coupling heads
Transmitting forces
Retracting lock
Locating spring

Lock spring
PA M of Returning lock
Permitting coupling
Keeping lock coupled

Cam
P.A.M of Retracting lock
Converting motion

Spindle·
PA.M of Transferring motion
Guiding plunger
Neutralizing
Applying load to torque spring
Locating cam and finger
Access for plunger peg

Operating finger·
PA.M. of Converting linear to angular motion

Neutralizing collar
PA M of Holding spindle
Guiding itself
Releasing plunger

Torque spring:
PA.M of Returning lever
Converting horizontal to vertical motion

Collar guide
PA M. of Guiding collar

Connecting pin
PA.M. of Connecting plunger to collar

Plunger peg
PA M of Locating plunger

Figure 21.7. Functional means provided by the partial design solution

For example, the plunger *H* and connecting pin *J* could be seen to move without doing any useful work. Similarly the twist of the spindle *F* intended to be resisted by the torque spring *I*, was seen to be an entirely unnecessary action that could quite easily be replaced by exploiting the reaction of the lock spring *E* on the cam C via the lock *D*. At last there was a really positive indication of both the location and the nature of the redundancies only dimly sensed before. How to remove the redundancies whilst maintaining essential functions became the major problem.

It is sometimes useful to be able to stand away from a piece of work in order to survey the whole vista and possibly by doing so to to see a new line of action. To this end, after careful consideration of the first three charts in relation to one another, a further chart was prepared to indicate in broad outline the operation of the coupler and track device, and the compatibility of various partial solutions. It must be emphasized at this point that no design sketches had yet been produced for a coupler or a track device, all work having

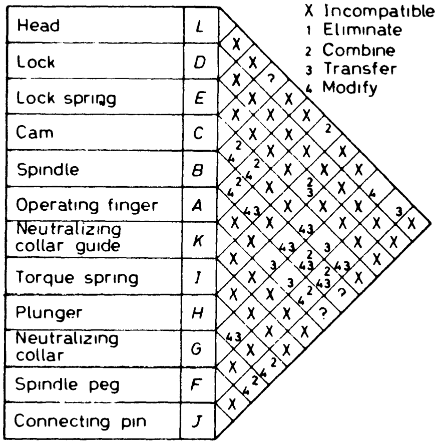


Figure 21.8. Study of the possibility of eliminating, combining or transferring items or whole sections of the design

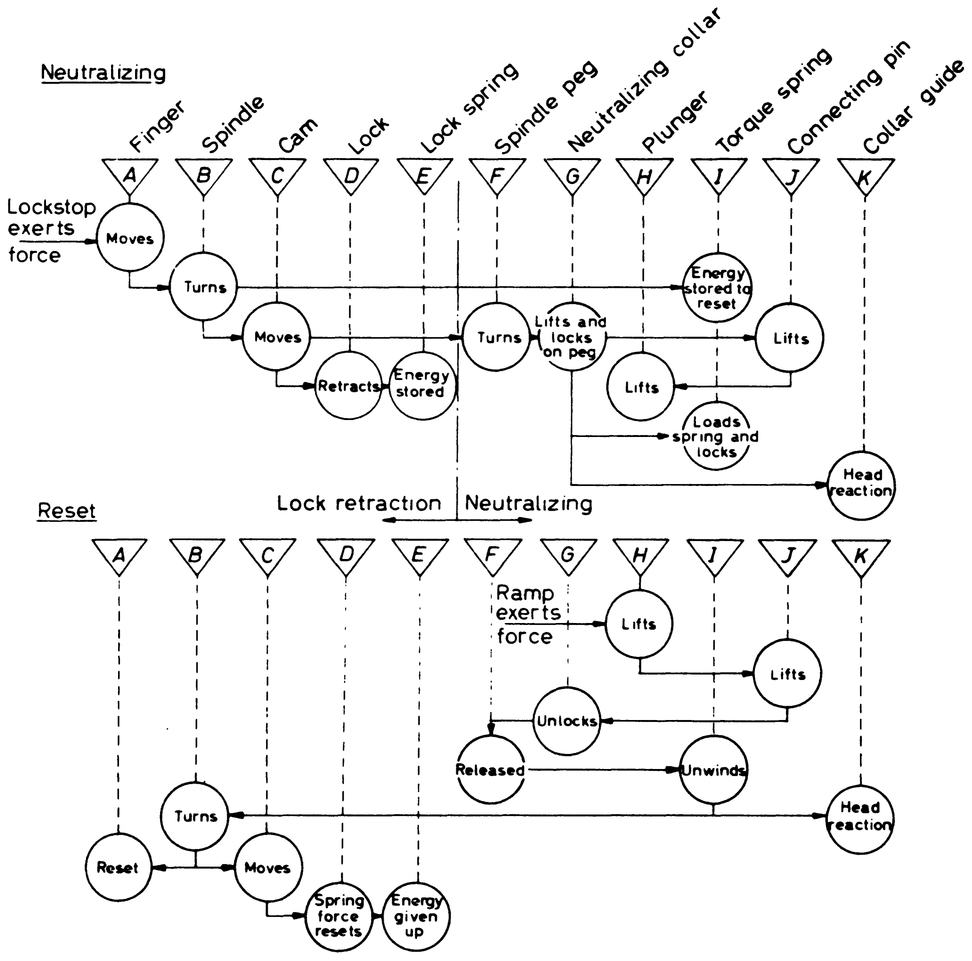


Figure 21.9. Functional process chart to show sequence of operation of design

been done with the aid of a single 'Heath Robinson' sketch and four extremely simple charts.

The fourth chart (*Figure 21.10*) helped to establish that the track device could be single action (one device to lock and one to unlock) or could be double acting (thereby locking and unlocking successively on the same device). The coupler 'branch' of the chart revealed an important but hitherto unnoticed 'obvious' point that while a coupler was locked by operating a finger, an entirely different part of the mechanism was operated to reset the coupler. The immediate thought triggered by this discovery was that the mechanism should be able to lock and unlock itself by the track device if only the operating finger *A* and plunger *H* could be combined. The redundancies that had been troublesome would then have largely disappeared.

This last thought was the breakthrough which had been looked for. It was confirmed when the functional process chart (*Figure 21.9*) was again studied. The closer scrutiny of this chart from the viewpoint of the new knowledge, revealed that items *A* to *E* were concerned with retraction of the lock and items *F* to *L* with the retaining of the lock in its retracted position. Using a functional process chart as shown in *Figure 21.11,* it was therefore argued that if the first five items were made self-locking the mechanism and head construction would be of a far simpler form.

Only at this instant was it realized where the design thought-process had been most clouded and wrongly influenced by previous designs. In all previous coupler designs the retraction operation had been locked by an additional mechanism be it a simple pin or a plunger device. Illustrations of these can be seen in *Figure 21.2*; these show the various stages in the development of methods of neutralizing previous couplers, *i.e.* temporarily holding the lock in the retracted position. In *Figure 21.2 (a)* the original coupler had a locking pin to drop into a recess in the lock. In *Figure 21.2 (b)* the operating lever is held in the retracted position by a lever mounted on the end of the mine car. The integral coupler illustrated in *Figure 21.2 (c)* uses a spring loaded plunger to drop in front of a projection on the lock after either of the two side levers has been pulled to retract the lock.

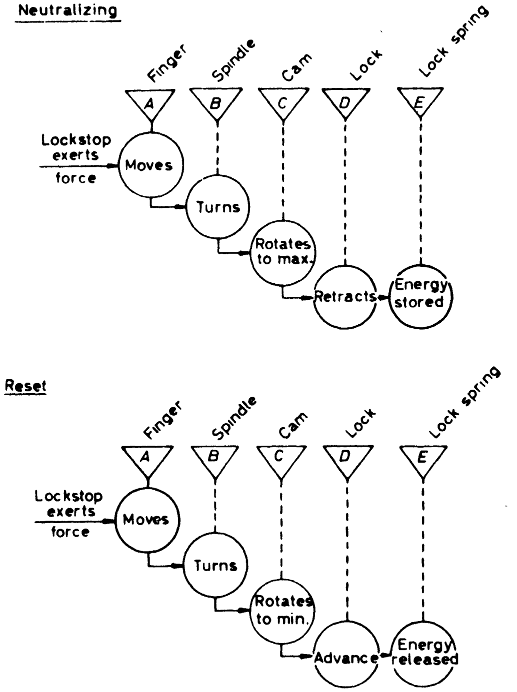


Figure 21.11. Functional process chart for new design

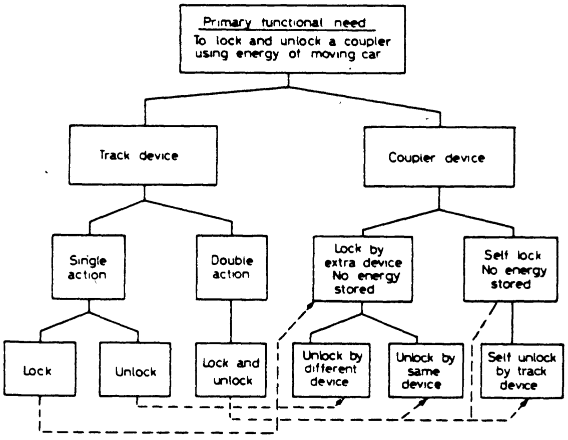


Figure 21.10. Operational variation of coupling and uncoupling device

This realization brings out the true advantage of charting one's thoughts and ideas whether or not they are subsequently rejected. In the usual design process, decisions are made and ideas rejected at every stage, and in many cases good designs are lost because one cannot call back ideas and decisions which have been made days or weeks earlier, and committed to the mind's waste paper basket. In this case it was possible to refer to the previous charts to confirm the decision that the coupler mechanism could be self-locking for simplicity. Without such charting one might well have been satisfied with operating only a halfway solution, namely a combination of plunger and finger instead of the complete elimination of fifty per cent of the entire mechanism. The ways and means were listed of providing a self-locking mechanism to be operated by the track device and employing the energy of the moving car. Thoughts on the requirements of the haulage circuit of the mine produced the idea that the track device should be capable of operating the coupler to lock or unlock when the coupler passed over it in either direction, permitting standard single symmetrical track devices.

Reverting to the self-locking coupler mechanism, consideration was given to various non-return devices resulting in a short list of four devices:

(1) *Toggle* – Would have to provide 1¼" in. movement at the lock and would occupy more space than was available within the coupler head and shank. The toggle would also require three pivots, possibly machined.

(2) *Cam* – Would be compact, may not require machining, and would fit in coupler head space. Could be 90° or 180° operation cam, *i.e.* double or single operation of lift per revolution. Could be affected by wear.

(3) *Worm and Wheel* – Would be precise but possibly expensive, and could be affected by dirty working conditions.

(4) *Friction* – The use of friction, which is variable and unpredictable, may not give a satisfactory solution. Additional effort would be needed to overcome friction before it could be used to lock the mechanism.

From this short list, the cam appeared to satisfy the greatest number of operational factors in the life cycle.

Considerable thought was now focussed on this possible solution and resulted in the proposed design for a 90° operation cam, although the possibility of using a 180° cam had not yet been entirely eliminated. This was the stage reached at the end of the course at Engineers' House when the proposed new mechanism was sketched out as in *Figure 21.12*.

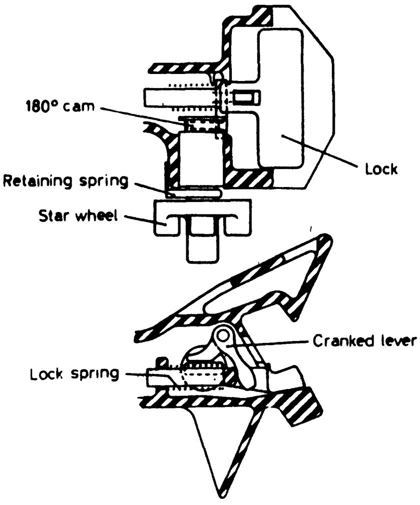


Figure 21.12. Proposed new design of coupler mechanism

Following theoretical studies of cam profile and motions, wooden models of the two cam operations were made and tried out for functional effectiveness. It was found that the 180° cam mechanism had a dwell in mid-motion and therefore the mechanism would be subject to two periods per cycle of acceleration and deceleration. This was undesirable from the point of view of increased wear. The 90° cam mechanism provided a smooth operation and was therefore adopted for further development. This stage of the process is illustrated in *Figures 21.13* and *21.14. Figure 21.14(b)* shows the much simpler replaceable stop of the 90° cam mechanism on the track device.

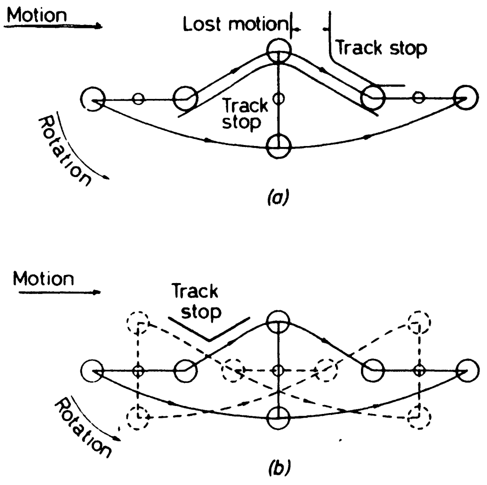


Figure 21.13. Study of motion of operating cams: (a) 180° cam, (b) 90° cam

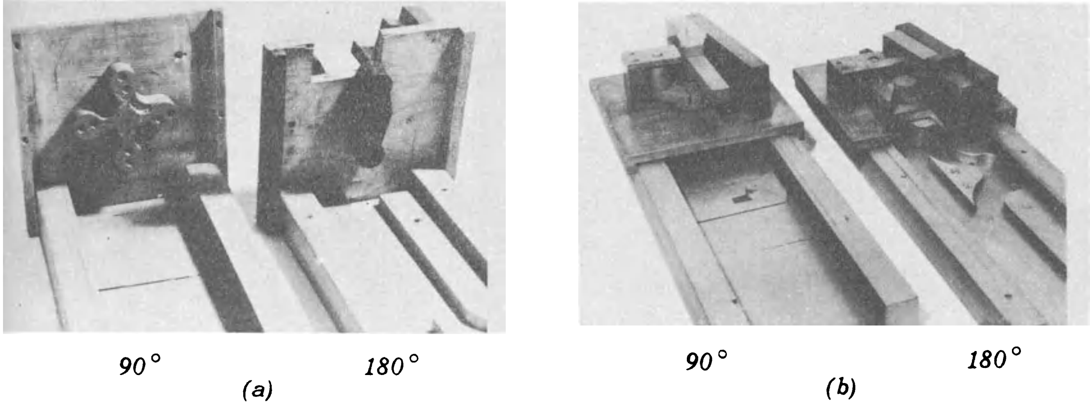


Figure 21.14. Wooden models to check operation of 90° and 180° cam mechanisms: (a) underside of coupler mechanisms; (b) inside of coupler mechanisms

To ensure the correct form had been used for the various parts of the mechanism a prototype coupler was produced from an existing coupler, which was split so that the side could be removed to observe the motion of the mechanism and to facilitate modification of the parts. This is illustrated in *Figures 21.15, 21.16* and *21.17*.

The relative positions of the cam and cranked lever during the neutralizing and reset conditions can be seen in *Figure 21.18*, which is a sectional plan view of two mated couplers.

To assist in the dimensional checkings of the production drawings for functional effectiveness, the chart in *Figure 21.19* was produced. This ensured that all the various interrelationships in the mechanism were

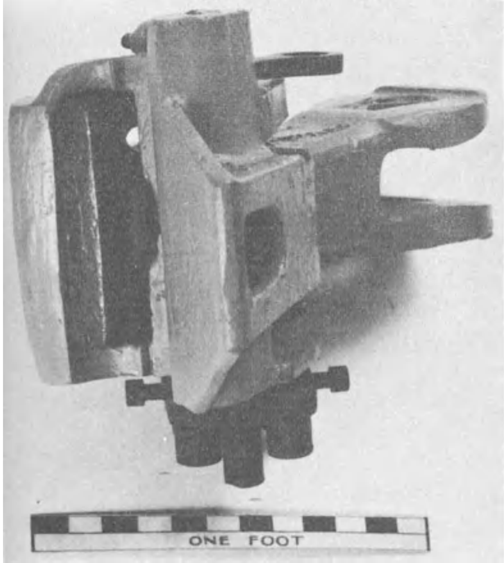


Figure 21.15. Prototype mechanical coupler

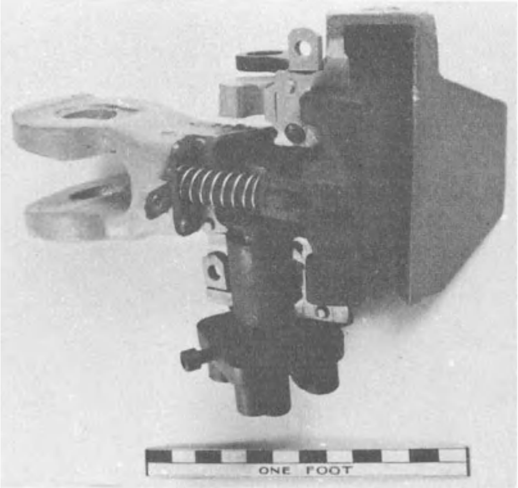


Figure 21.16. Prototype mechanical coupler with side removed to facilitate inspection and modification of the internal parts

investigated for clearance, effect of production tolerances, *etc.* In addition the possible effect of a change in any one item on other associated items was immediately apparent. As each relationship was investigated the appropriate code number was entered into the corresponding square, and where there was no direct or indirect relationship the square was blanked off. (The chart shown in *Figure 21.19* was also used to check a hand operated integral coupler design which was developed to replace an existing integral design.)

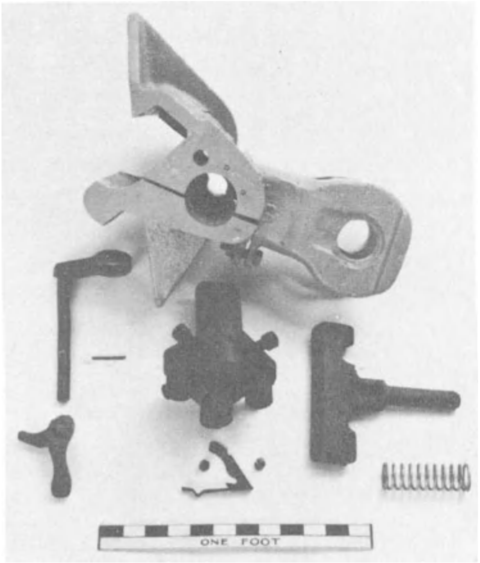


Figure 21.17. Bottom view of prototype mechanical coupler with a display of the parts of the mechanism

This completed the design for the coupler device.

Attention was next focused on the installation and operational aspects of the introduction of the mechanical coupler to a mine circuit. This was a complex problem in that the factors influencing the siting of the track devices varied from mine to mine. To facilitate this part of the investigation, several schemes were drawn up and each scheme was charted as shown in *Figure 21.20*. Each scheme was checked against the operational factor to determine *(i)* the effect of the scheme upon the operation, and *(ii)* the effect of the operation on the scheme. This brought into the open many points which had previously been hidden. The chart shows only a few of the many questions asked and answered during the investigation of several different schemes.

It will be seen that the idea of symbolizing one's thoughts in the form of simple charts

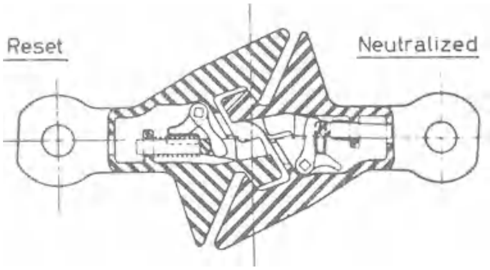


Figure 21.18. Sectional view of two mechanical couplers in neutralized and reset condition

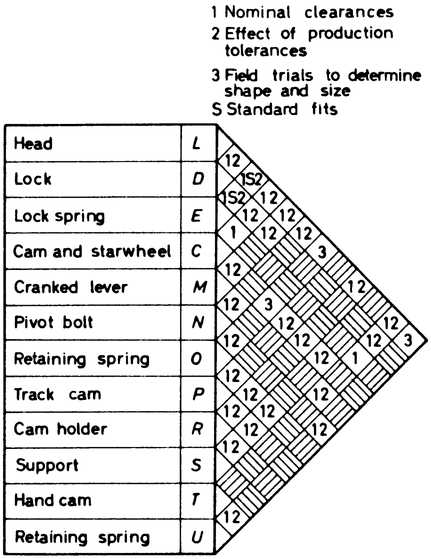


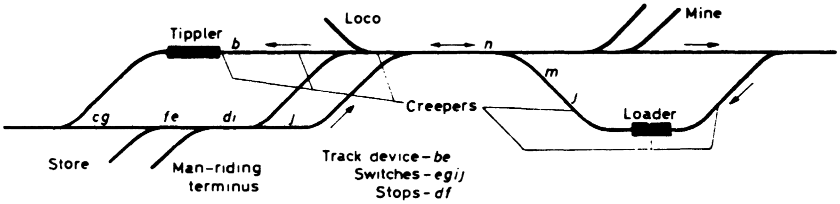
Figure 21.19. Chart to check functional effectiveness of the mechanical coupler and track device

to aid the particular stage of working was exploited right up to the completion of the design study.

In *Figure 21.21* the various factors affecting each scheme have been given a rating, and the total sum of these has been used to produce a histogram. From this the overall value of each scheme may be compared with each other and with the ideal. From *Figure 21.21 (a)* it can be seen that scheme V in this instance was preferred although it was still not ideal. Reference to *Figure 21.21 (b)* enables one to evaluate which part of the scheme could be improved or further refined.

Figure 21.22 is of a mechanical coupler installation showing the relationship of the track device to the coupler which is mounted on the mine car underframe. In this installation the track device is held horizontal at the correct height by a spring contained in a telescopic casing. After operating the coupler mechanism the track device is depressed below the level of the car underframe by the car axles and returns to normal height when the car has passed forward. This is required because the coupler operating gear is located above the axle level as a means of protection against accidental operation by debris on the track.

Throughout the project an attempt was made to consciously steer towards good design, *i.e.* the *optimum* solution to the *sum* of the *true needs* of the *particular* set of circumstances. Besides the very thorough consideration of functional needs, far more detailed attention was given to customer and company needs than in normal design practice, partly again by the use of appropriate charting.



Effect of scheme I on operation	*Operation factors*	*Effect of operation on scheme I*
	(1) Locomotive movement	
	(*i*) Exit and entry to circuit	
o k	Loco shed	o k
o.k.	Workshops	o k
Use track occupied by 1st train	Material stores	Switches *i* and *j*, stop *e* retracting
o k.	Man-riding terminus	Retract switch *j*; resite terminus
o.k.	Mine terminus	Will mech'l coupler go into mine?
	(2) Input of cars to circuit	
o k.	(*i*) Workshops	(*i*),(*ii*),(*iii*) must cross *j*
Reposition, relay track	(*ii*) Material stores	(*i*),(*iii*), must be 32 car train
o.k.	(*iii*) Man-riding terminus	
?	(*iv*) Mine terminus	?
	(3) Removal of cars from circuit	
None	Points possible	Drift, loco shed, stores, terminus
"	Points essential for correct op.	o k except cement store exit
	(4) Derailment reducing train length	
Not less than 32 cars hauled	Effect on schemes	Train will not span creepers
?	Increase length of trains?	

Figure 21.20. Investigation of field application to determine siting of track devices and method of operation

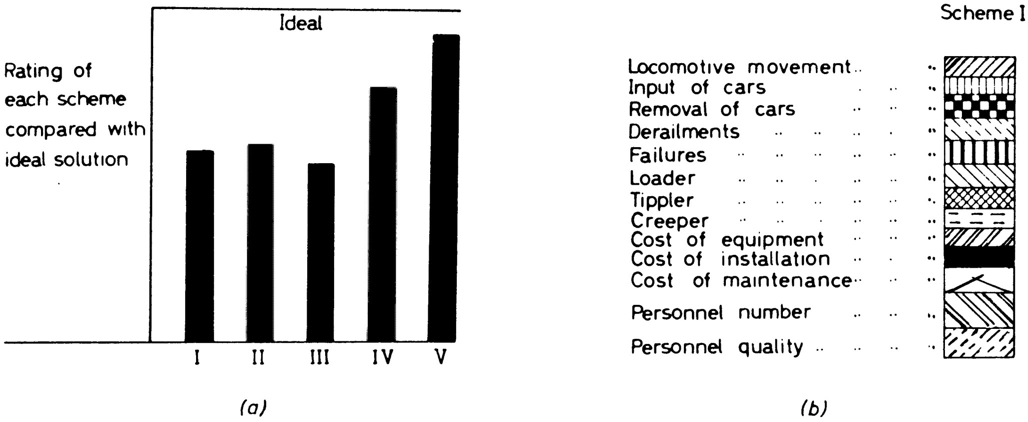


Figure 21.21. (a) Histogram showing the relative values of various schemes for the application of mechanical couplers; (b) details of one scheme forming part of the histogram

The new coupler is now being produced and shows every sign of being very successful.

It has not been possible in this brief account to describe adequately how the abstract concepts of the nature of the design aims, processes and elements assisted either the choice of charts used to symbolize thoughts, or the methods of analysis and synthesis. The fact that much of the fundamental design method is concerned with a study in depth of the essential nature of good design, and that this study continues in parallel with the work on the actual design project should not, however, be overlooked in evaluating the results of this project. Similarly those who wish to improve their own design approach by private study, may well benefit from paying as much attention to the various characteristics of the course as to those of the formal 'techniques' revealed.

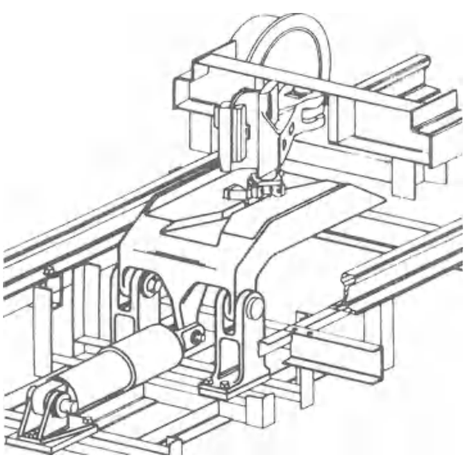


Figure 21.22. View of track device installation and a mechanical Willison coupler

Possible Misunderstandings of the Nature and Practical Value of Abstract Concepts used in Fundamental Design Method

The process involved in designing is basically one of *applying* knowledge to visualize and judge. The ability to produce designs which satisfy an amalgam of needs in an optimum way is as much related to the methods of applying knowledge itself. Unless and until knowledge is organized around the basic needs of a design situation, and the designer becomes at least partially aware of the fundamental characteristics which all design problems and processes have in common, he cannot begin to apply knowledge in a really effective way.

Fundamental design method is not primarily a simple problem-solving procedure. It is more a way of working which involves a high degree of awareness of one's own mental moves, coupled with an awareness of abstract concepts of the essential nature of good design and the design decision process. These concepts which a designer can learn to refer to rapidly at will and use as 'absolute' standards are constructed initially by a process of deep reflection around partial concepts proposed on the course. Before they can become meaningful and therefore truly useful, the designer concerned must be prepared to attempt to express his own experiences in an abstract form, and this is by no means easy.

Improved methods which will arise from such examination will necessarily differ in many respects depending upon the persons and design project involved. The PABLA system used at the United Kingdom Atomic Energy Authority, Aldermaston, has received wide publicity and can easily be misread as a universal system for designing, which it was certainly not intended to be. PABLA began as a project on the fundamental design method course and has been developed in close collaboration with Engineers' House, who help to train all UKAEA designers in its use.

Although derived from fundamental design method, PABLA does not necessarily require the individual to possess a high degree of awareness of his working method or abstract concepts of the type mentioned, and its aims are more limited. While PABLA is intended to achieve a degree of improvement throughout an organization by simple prescribed procedures related to certain areas of design work, fundamental design method relies on a heightened awareness on the part of the individual, as well as his continual use of abstract concepts, to determine the most appropriate actions throughout the entire design process. In other words it requires a kind of thinking which is significantly different from traditional design thought.

The concepts used in fundamental design method may be said to be derived from digested experience, whereas the designer's intuitive mental moves will stem from his undigested experience. Ar first the concepts will almost certainly suggest changes in approach that 'feel' incorrect. Although the designer has to be very careful in the learning stages to check that the concepts are not indeed in error, he must be prepared to *use* them until they are proved wrong, and to go on correcting and refining them until they can be relied on completely. Hence theory and practice continually interact on each other and become a most advantageous living partnership.

Chapter 22

DESIGN REALIZATION

F. L. Ellis

Introduction

The aim of this chapter is to discover generalizations of value concerning the process of design realization so that the tasks of designers may be better comprehended and studied. In approaching this it is only too obvious that experience in restricted areas of specialization will tend to be drawn upon. Clearly, builders and civil engineers will tend to specialize in one way; production engineers will specialize in another way.

Design realization is concerned with the practical tasks of converting a design idea into a working entity. In some form or another this working entity is expressed in materials. The materials are chosen to provide the basis of the functions that the product has to carry out. These materials have to be provided with a practical shape and this is done during the fabrication process. The selection of materials is therefore not solely a question of product function but of the ability to provide the shape required. Clearly, fabrication method may influence design. Consider, for example, the difference in approach needed for traditional building and industrialized building.

An important feature of modern products is that many of them are assemblies of parts of various kinds. This is implicit in most engineering system products. The procedure for assembly may constitute an imposing part of the total realization operation. This is particularly true for the two extreme kinds of system commonly manufactured: flow products such as consumer durables, *e.g.* motor cars; complex one-off products, such as oil refineries, nuclear and other power plants, chemical factories. In the case of such assemblies there may be a clear interest in avoiding the direct problems of fabrication proper of parts or components. In spite of this the overall design has to be accomplished in such a way as to facilitate assembly, although correct function is the final aim.

In addition to integration of the design idea in terms of materials, fabrication and assembly, thought has to be devoted to the effect of these operations on the function of the product in order to provide the necessary function. This again is increasingly concerned with system behaviour, with reliability.

To obtain realization in a material embodiment, certain instructions must be passed. The provision of the technical information for these instructions is commonly a principal function of the drawing office, although, depending upon the industry and the company, the drawing office may have other functions earlier in the design sequence.

The relationship between materials, fabrication, and assembly is now considered.

Materials and Systems

Various ways may be used for categorizing materials but, in the present context, it is convenient to use an approach based on system function. By system function is understood the main action of the system: the kind of transformation brought about by the system whereby the input emerges as an output.

It has been said that systems may handle energy, mechanical motion, chemical operations, or information. In practice, systems tend to be complex and usually hybrid. For example, an electrical generating station may contain a chemical system (the combustion sub-system), a thermodynamic system (the sub-system in which heat is converted into rotary motion), and an electromechanical system (the sub-system in which rotary motion is converted into electrical energy). There are also other parts of the major system, each with its immediate containment and supports, and the totality of these is interlinked and contained as necessary.

As a mechanical engineer my interest tends to lie in the field of kinematic systems, but I have interests in thermodynamic systems, particularly refrigerators, and in the containment of pressure systems, as involved in steam-raising or in many types of chemical process.

In machine design the materials of construction play a great part directly in the system transformation process, as well as contributing to enclosure and support. In many prime movers there are temperature and corrosion problems to be solved, as well as the pressure situation to be dealt with. Aircraft and space propulsion units bring further problems: the need for lightness, and possibly the handling of exotic fuels.

Machine Design

In the case of machine design a methodical approach will include: *(a)* searching for an existing solution to a similar problem; *(b)* looking at books which include examples, preferably in collections, of already developed mechanisms; *(c)* attempting to obtain solutions by combining known constructional elements.

It is likely that a number of solutions will emerge, some of which may be eliminated immediately. If a number appear to have equal merit a methodical evaluation process is advisable. A method which enables a choice to be made quickly is given by MATOUSEK (1963). This consists of allocating points for all the conditions which the problem requires to be fulfilled. The best solution is the one that has the largest total number of points; its closeness to an ideal solution may be expressed in the form of a merit rating, as the ratio of the number of points awarded to the number obtainable.

A small difference in a large total would not be considered significant and a further evaluation, allowing for the relative importance of the original conditions, would normally enable a final choice to be made. If they still prove to be of almost equal merit it would be advisable to proceed with detailed design of both until it became clear that one of them was markedly superior.

When the kinematic scheme has been decided upon, the designer is ready to begin the task of accurately determining the material, the manufacturing processes, and the dimensions (with tolerances) for each component. This is achieved only after a considerable amount of trial and error work, since the components are interdependent and the decisions made with regard to one will affect those made concerning another. (This highly detailed interdependence, demanding many small decisions, may well occur in other branches of technology, *e.g.* electronics.) Characteristically a few decisions are tentatively made, the effect of these on others is checked, and necessary adjustments are made. This procedure is repeated until the design eventually reaches completion.

The design of the contact members provides suitable starting points, since in many instances they control the design of the other components. Contact members include gears, cams, chain and belt drives, brakes, clutches, and springs. The shafts for supporting the contact members may then be designed. This is frequently done on the basis of shaft deflections, since these will be limited by the engagement requirements of the contact members (in the case of gears, for example, it is desirable to have good load distribution across the face width), or by clearance requirements between moving members (*e.g.* between the rotors and stators of electrical machines and turbines). The shafts cannot be designed without, at the same time, decisions being made regarding the bearings and the bearing lubrication system. When these have been taken into account the proposed shaft must be checked for strength, including the possibility of failure due to fatigue.

None of the decisions in this sequence can be taken without knowledge of, or assumptions concerning, the materials to be used.

The frame of the machine and the links which transmit the forces and motions from the contact members to the other elements may then be designed. The frame has to be strong enough to transmit the reaction forces to the foundation and rigid enough to provide reasonable alignment between the moving parts. The absorption of vibration by damping may be necessary. Again, in each of these points, materials must be considered.

In addition to obtaining a solution which will not fail while providing the service expected from the machine, the designer tries to obtain the best solution. This is usually achieved by making decisions which result in a compromise between a number of conflicting but desirable attributes.

Successful designs in different fields of activity are brought about by the application of different design philosophies, *i.e.* attitudes which arise from the relative importance attached to the factors which must be considered. Thus the attitude of the aircraft designer will differ from that of the car designer and from that of the ship designer (EDER and GOSLING, 1965; FAIRES, 1955). These attitudes are reflected not only in the basic design constraints but also in the approach to the use of materials, to fabrication methods, and even to assembly methods.

Choice of Materials and Fabrication Methods in Design

When a machine component is being designed, the processes by which the part is to be made must at the same time be considered. The designer has to be familiar with such interdependent factors as the suitability of materials for various fabrication processes, the effect of the processes on the subsequent properties of the material, and the design details involved in the process. The shape of a component is often determined by the properties of the material and the manufacturing process (TWEEDDALE, 1962). For example, ordinary grade cast iron has a poor tensile strength but high compressive strength. If it is used for a member which is subject to bending, such as a cantilever, this would be designed with a cross-section which utilizes the high compressive strength but keeps the tensile stress to a low value. The cross-sectional shape would also be influenced by the necessity to provide draught angles so that the casting could easily be removed from the mould. Generous fillets or radii would also be required.

Where no specific requirements for materials are stated in the problem given to the designer, he has the responsibility of listing all the factors involved and making choices based on them. The most suitable materials may be chosen by using an evaluation plan in conjunction with an extensive list of factors (Matousek) or by employing a system involving optical coincidence feature cards (SELWYN, 1965).

In some cases the number of materials that will satisfy the function requirements with reasonable economy will be small. For example, there are relatively few material combinations suitable for worm gearing. Where loads and rubbing velocities are high it is usual to employ centrifugally cast phosphor bronze for the wheel and nickel–chromium alloy or nickel–chromium–molybdenum alloy for the worm. As another example, the tubes in heat exchangers are normally required to have good thermal behaviour. If mild corrosion is present as well the choice of material may be restricted to aluminium, brass of some kind, or copper. In the case of highly loaded spur, helical or bevel gears, cams and followers, and sprockets and chains, the controlling factor is likely to be surface failure and this would point to the use of case-hardened steel.

With electrical functions the choice is usually heavily restricted, and in complex systems it is made more difficult. For instance, the squirrel-cage rotors of fractional horsepower cartridge-type motors, used in hermetically sealed refrigerator systems containing dichlorofluoromethane as refrigerant, may have either copper or aluminium conductors in the slots; the former leads to the use of brazed-on end rings, and the latter to the use of end rings cast integral with the conductors. Aluminium would need to be free from magnesium to avoid possible chemical reactions involving the refrigerant.

In some cases the selection of a material is rendered difficult on account of the large number of possibilities. These are often cases where the forming, welding, or machining processes demand sizes which are in excess of those required for adequate strength and stiffness, either for function or other purpose. If the material value is high and there are other advantages to be gained, there will be much pressure to change manufacturing processes. This may be seen in the recent drive to microminiaturization.

There are certain rigidities involved in materials selection. Apart from the general pressures in industry to provide a safe solution the designer has usually had special experience with some kinds of material. He has designed components from them and the results have been satisfactory. He is therefore naturally disposed towards using them whenever he can. Further, he will be influenced by the availability of fabrication facilities, particularly in his own company. He will normally be reluctant to incorporate new materials into his designs until they have been satisfactorily demonstrated to be superior to the ones which he normally uses, or to those found doing similar work on other equipment. He will tend to stick to established practice and resist change whenever in doubt.

Fortunately there is a development potentiality in most designs. Somewhere it is usually possible to try out new materials in a practical way on current products. This gives the opportunity for trying new materials under known conditions of operation before exploiting their characteristics to provide designs not previously feasible. Designers who act systematically in a conservative way have a responsibility to bring forward and exploit new materials in the same methodical manner.

Fabrication, Assembly and Design

The selection of materials and associated processes is, of course, influenced by the quantity of components or number of systems to be produced. It is unlikely for example that patterns would be made for the production of, say, four cast iron gears if, as is likely, suitable forged steel blanks could be easily obtained. There are, however, cases where patterns are made for one or two castings, a typical one being the drawing dies for producing panels of motor car bodies. In this case fabrication does not provide a suitable product as pattern. The panels of mass-produced motor car bodies are butt-welded in a flash-welding machine. Where quantities are small, instead of this machine and the design associated with its use, it is common to use a spot-welded lap joint (joggle joint) which is filled with solder and then finished off to present a smooth outer surface.

The shape of a steel cabinet is often box-like because the quantity to be made does not warrant the production of the special tools needed to make a more interesting shape.

Not only does the designer need to consider the cost of material and the cost of fabrication and assembly (machines, conveyor systems, and labour) but he has also to consider the cost of design. The amount of time that may be spent to detail work on a design, broadly depends upon the type of project, *i.e.* whether it is a simple one-off job, a complex one-off job, a batch production, or a flow production. This applies to the calculations connected with the design of the product in addition to the information issued with regard to its manufacture.

It is in this area that advantage may be drawn from the use of standard components, by reliance upon drawing office practice, and by the exploitation of a close knowledge of particular workshop practice.

Flow Production

In many cases flow production involves large capital investment in connection with the manufacture of a low or moderate cost consumer product. In order to protect the investment and make profits it is important that the product should give reliable service within at least the warranty period and be available at a competitive price. The effective achievement of these ends requires painstaking attention to detail design in connection with function, appearance, transportation and production. In addition there must be adequate quality control during production.

Quantities are so large that the product designer, in order to achieve an optimum design, does not concern himself too much about incorporating standard components of the type which are usually available at engineering stockists. He will, however, think in terms of standard pieces such as bolts, nuts, rivets, washers and split pins, and of standard intermediate materials such as wire, tube, bar, sheet and plate, which are themselves the results of large-batch or flow production.

One may view flow production as a particular method of solving an assembly problem. This method is then supported by some method of obtaining the necessary parts and components. These may be purchased from an outside supplier or made directly. In turn, whether in an outside factory or at the main works, the parts may themselves be produced by some selection of flow processes. In order to secure fabrication that is highly economic it is sometimes necessary to install special purpose machine-tools, often with automatic transfer equipment between them. There is a trend now towards multiple-operation machine-tools in order to diminish transfer requirements.

With increasing emphasis upon economy of operation in flow processes attention is being directed to methods of economizing in the use of raw material stock. This may lead to rethinking about the method of fabrication employed, and thence reflection on the original component design.

Flow production tends to modify the fabrication processes and auxiliary operations. Thus, instead of brazing a number of bushes into a casing separately with a hand-torch followed by cleaning by shot-blast, a preferred method would be to employ furnace-brazing under a suitable protective atmosphere to avoid subsequent cleaning. This would not only permit the use of less skill but would provide a more consistent level of quality. Similar results follow from the use of automatic arc-welding, replacing manual methods.

Special auxiliary plant may have to be developed to keep the flow moving. In the manufacture of domestic refrigerators, for example, equipment is needed for dehydrating the units to avoid decomposition of refrigerant, for de-aeration of the oil to be used as lubricant, and for charging oil and refrigerant into the systems.

Prototype models should be made to match as closely as possible to the product that will eventually be mass produced, because the time available between the making of the first products from tools and the beginning of mass production is frequently inadequate for rigorous testing. This means that the parts for prototypes should be made from drawings which closely resemble those to be eventually issued for tooling up the product. Even when this is done, there is difficulty in obtaining prototypes which correspond in quality to the products made in bulk since the former tend to be made to high standards by skilled craftsmen. There would seem to be some scope for laying down specifications which give prototypes with behaviour more akin to the products of the flow line.

Batch Production

This classification covers products ranging from large system units such as aeroplanes, to simple machine components for which there are unlikely to be sufficient orders to warrant continuous production.

In a large number of cases batch production is characterized by the use of standard machine-tools and general purpose processing machinery. Different parts tend to be made by retooling automatic lathes, changing the cutters and fixtures on milling machines, changing the drills and drill-jigs on drilling machines, changing the dies in presses, *etc.* This type of operation can be particularly difficult. Not only are many detail drawings needed, but the complexities of planning to get the best utilization of machine-tools and delivery of the components and parts in the right sequence, at the right time and to the standard specified, produce many problems of an intractable nature.

Since much manufacture falls within this class there is a sound case for exploring and exploiting the various possibilities for reducing difficulties. The use of standard materials, standard parts and standard components available to industry at large, helps with this kind of work. Thus, when designing compressors for use on commercial refrigeration plants, it might be desirable to try to use as many components as possible from models mass-produced for domestic purposes. The limiting design then might well be a three-cylinder radial compressor (two cylinders for some applications) incorporating the pistons, grudgeon pins, connecting rods, valve plates, cylinder heads and gaskets designed for the domestic model. It may also be possible to use other common items such as terminals for connection to the leads of the electric motors. In a larger unit it may be possible to use connecting rods mass-produced for motor car engines.

It is in this class of manufacture that the maximum advantage may come from numerical control of machine-tools. There is the possibility of saving in setting time and skill, and from the re-use of prepared programmes.

Anyone who has spent time in the works is only too conscious of the need to find some way of dealing with the problem of planning and progressing. Research in this area should be strengthened with a view to reducing the large commitment of human resources and the frustration so typical of this kind of work.

Simple One-off Jobs

Press-tools, jigs and fixtures are typical examples of one-off jobs. They are usually made to detailed drawings and exploit stocked materials and standard parts (some of which may be internal company products from batch production). Parts might include drill bushes, screws, dowels, clamps, and springs. Stocked materials would include a selection of commercially available rods, bars and plates. These parts and products are then used for making items for batch or flow production.

Such one-off items may be made in a simple jobbing shop or, in the case of tooling items, in the tool room. Where possible, advantage is taken of a knowledge of shop practice in the specific case. Typically tool designers may be expected to have served an apprenticeship in the tool room and in other aspects of tool-making.

Tooling items tend to be designed on the basis of experience, the greatest requirement apart from low cost being sufficient rigidity. A job may consist of little more than the manufacture of a frame to support a number of pieces of commercially available equipment. Although the job itself may seem simple the system design may be complex.

Many one-off jobs come from people who specialize in a particular kind of fabrication process. The items manufactured are often to be used in more complex assemblies brought together by other organizations. For example, heavy work such as the fabrication of pressure vessels, or the production of items in special materials such as stainless steel, aluminium, or certain plastics, tends to be the field of a restricted number of manufacturers who keep their position by the possession of special skill or skill with necessary equipment.

In general, there is a line of development in which such specialist manufacturers attempt to take advantage of their skill and to widen their outlets by introducing the design of products which particularly require their facilities. Pressure vessel manufacturers, for instance, move towards the manufacture of steam-generating equipment, heat exchangers, and certain items of chemical plant. In their normal one-off trade they are required to assist in the optimum design of their customers' items. As an almost natural consequence the build-up in design skill leads to self-generated design. Here is a case of fabrication causing the development of design.

Complex One-off Jobs

These are essentially system projects with high capital cost of the type mentioned at the beginning of this chapter. Although the more expensive heavy plants are largely constructed from one-off or similar purpose-designed units there is always the pressure to use standard units. This pressure increases as the capital cost of the system is forced down or the number of units in a system increases.

It is usually an obligation that the system works efficiently and promptly, with the minimum of modifications after erection. For this reason the design is usually worked out in great detail, although, for practical and other reasons, this detail may arise from previous experience in one way or another.

In operations of this type which involve the building up of substantial teams for the execution of each stage of the project, a high degree of organization is required in order to make the best use of skills and the time available. From companies employed in this kind of operation comes much of the pressure for standardization in design procedure, for the acceptance of standards and specifications of wide industrial currency, and for the application of computer methods of design. Characteristic of this class of engineering is the exploitation of critical path methods in the solution of the assembly problem. Although by definition each assembly is different, investigation is beginning to show rational patterns with the possibility of building up computer programmes for each occasion from existing modules. In such a procedure the design of the management technique begins to show a parallel to the design method for the product itself.

Conclusions

The tasks of design realization lend themselves to analysis and the development of suitable systematic approaches. In some regions of the subject this has already been done, largely in an informal way; but the possibility exists of presenting the field in its totality, showing the range of approaches in several directions. This will enable a more rational development of the subject and will reveal new possibilities in the course of the enterprise, stimulating some people by the mere mention of techniques employed in a different class of business.

As with all systematic approaches the designer will still have to deploy his fundamental skills. The number of cases where design may be made entirely by system are certainly few, but they are useful and their number will increase (British Standards 537 and 436; BROWN, 1953). An example is given in the Appendix.

APPENDIX: Spur Gear Design

A 5 h.p. electric motor, with a shaft speed of 1,450 rev/min at rated power, is to drive a shaft at approximately 290 rev/min. Design a pair of spur gears with a momentary overload capacity of three times the continuous rating of the motor, and a centre distance of approximately 3·5 in.

For the required momentary overload capacity:

$$\frac{\text{Strength rating}}{\text{Wear rating}} = 1{\cdot}5 \text{ (see Clause 67 in B.S. 436)}$$

Pinion speed n = 1,450 rev/min

Wheel speed N = 290 rev/min

$$\text{Gear ratio } R = \frac{n}{N} = 5$$

Also,

$$a_p = \frac{X_{cp}}{X_{bp}}$$

and

$$a_w = \frac{X_{cw}}{X_{bw}}$$

where X_{cp} and X_{cw} are the speed factors for wear for the pinion and wheel, respectively; X_{bp} and X_{bw} are the speed factors for strength for the pinion and wheel, respectively. From the Forged Steels Chart No. 1 (shown in *Figure 22.1*), a_p = 1·0 and a_w = 1·0. Therefore

$$\frac{a_w}{a_p} = 1{\cdot}0$$

$$\delta_1 = \frac{\text{Strength rating}}{\text{Wear rating}} \times \left[\frac{1+R}{2C}\right]^{0{\cdot}2} \times a_p$$

where C is the centre distance. Therefore

$$\delta_1 = 1{\cdot}5\left[\frac{6}{7}\right]^{0{\cdot}2} \times 1{\cdot}0$$

$$= 1{\cdot}454$$

Using *Figure 22.1,* the point for R = 5 and δ_1 = 1·454 lies to the left of the a_w/a_p = 1·0 line. The number of pinion teeth required will therefore have to be read from Forged Steels Chart No. 2 (shown in *Figure 22.2*).

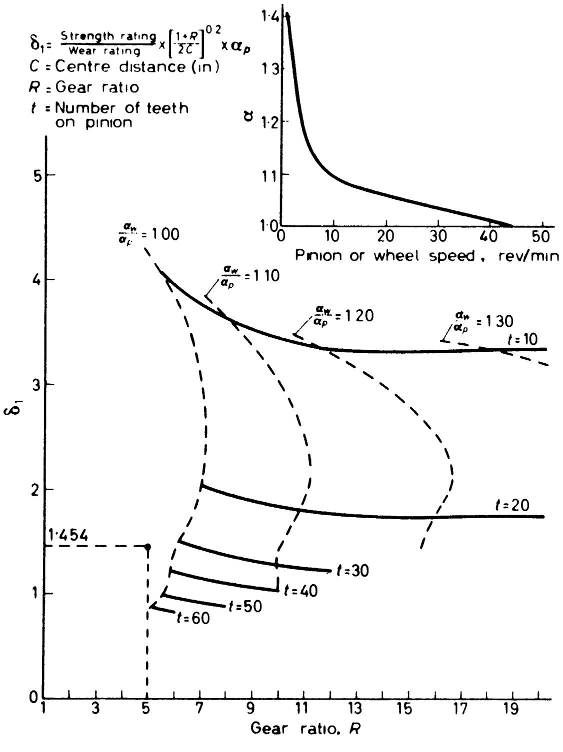


Figure 22.1. Forged Steel Chart No. 1

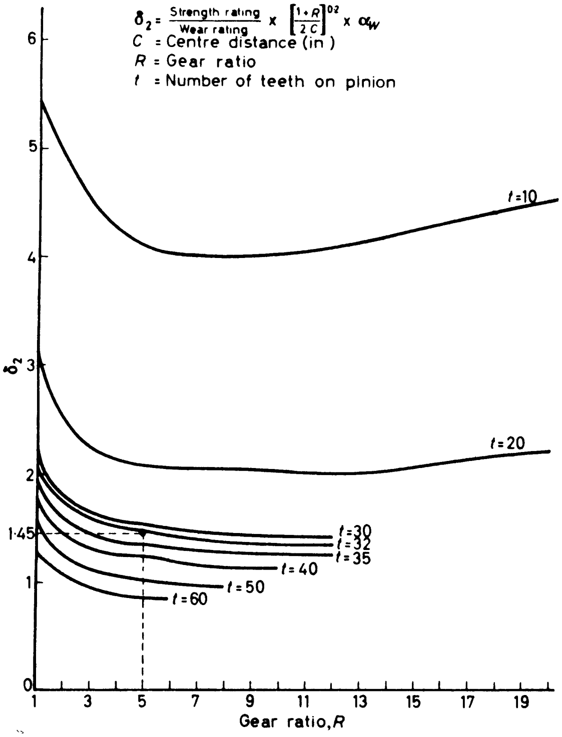


Figure 22.2. Forged Steel Chart No. 2

Using *Figure 22.2* the point for R = 5 and

$$\delta_2 = \frac{\text{Strength rating}}{\text{Wear rating}} \times \left[\frac{1+R}{2C}\right]^{0{\cdot}2} \times a_w$$

$$= 1{\cdot}454$$

leads to the adoption of 32 pinion teeth (t = 32).

$$\text{Number of wheel teeth } T = Rt$$

$$= 5 \times 32$$

$$= 160$$

$$\text{Diametral pitch } P = \frac{T+t}{2C}$$

$$= \frac{160 + 32}{2 \times 3{\cdot}5}$$

$$= 27{\cdot}43$$

Adopting a standard diametral pitch of 26, gives:

$$\text{Centre distance } C = \frac{160 + 32}{2 \times 26}$$

$$= 3{\cdot}7 \text{ in.}$$

Pinion torque rating required

$$\text{for wear} = \frac{63{,}000 \times 5}{1{,}450}$$

$$= 217 \text{ Lb. in.}$$

$$\text{for strength} = 1{\cdot}5 \times 217$$

$$= 326 \text{ Lb. in.}$$

$$\text{Pitch circle radius of pinion} = \frac{t}{2P}$$

$$= \frac{32}{52} \text{ in.}$$

$$\text{Circular pitch } p = \frac{\pi}{P}$$

$$\text{Maximum face width of pinion} = 5p$$

$$= \frac{5\pi}{P}$$

$$= \frac{5\pi}{26}$$

$$= 0{\cdot}604 \text{ in.}$$

Tangential force per inch of facewidth

$$\text{for wear} = \frac{217 \times 52}{32 \times 0{\cdot}604}$$

$$= 585 \text{ Lb./in.}$$

$$\text{for strength} = \frac{326 \times 52}{32 \times 0{\cdot}604}$$

$$= 877 \text{ Lb./in.}$$

Basic surface and bending stress factors required

$$\text{for pinion} \begin{cases} S_{cp} = \dfrac{585 \times P^{0{\cdot}8}}{X_{cp} \times Z} \\[2ex] \quad = \dfrac{585 \times 13{\cdot}55}{0{\cdot}24 \times 3{\cdot}3} \\[2ex] \quad = 10{,}000 \\[1ex] S_{bp} = \dfrac{877 \times P}{X_{bp} \times Y_p} \\[2ex] \quad = \dfrac{877 \times 26}{0{\cdot}246 \times 0{\cdot}795} \\[2ex] \quad = 116{,}500 \end{cases}$$

$$\text{for wheels} \begin{cases} S_{cw} = \dfrac{585 \times P^{0{\cdot}8}}{X_{cw} \times Z} \\[2ex] \quad = \dfrac{585 \times 13{\cdot}55}{0{\cdot}334 \times 3{\cdot}3} \\[2ex] \quad = 7{,}200 \\[1ex] S_{bw} = \dfrac{877 \times P}{X_{bw} \times Y_w} \\[2ex] \quad = \dfrac{877 \times 26}{0{\cdot}34 \times 0{\cdot}705} \\[2ex] \quad = 96{,}000 \end{cases}$$

There are no forged steels with permissible factors as high as these. Therefore case-hardened steels must be tried.

Using Case-hardened steels Chart No. 1 (*Figure 22.3*), the point for $R = 5$ and $\delta_1 = 1{\cdot}454$ lies to the right of the $\alpha_w / \alpha_p = 1{\cdot}0$ line and

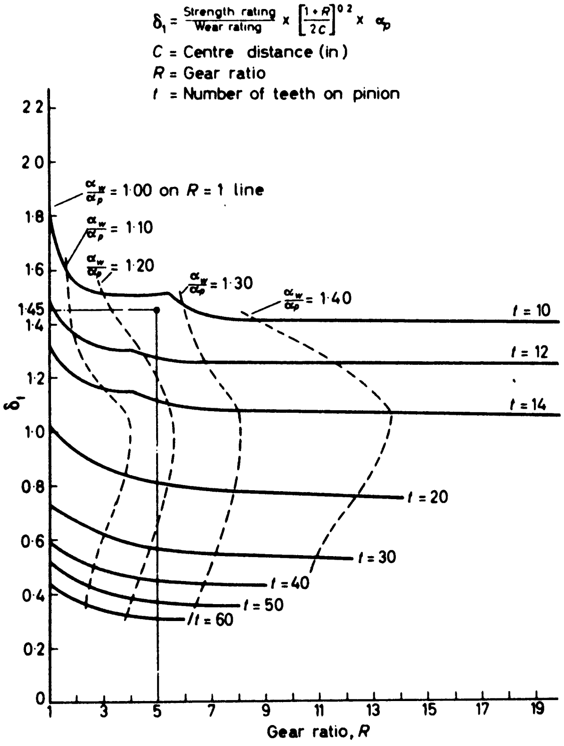


Figure 22.3. Case-hardened Steels Chart No. 1

leads to the selection of $t = 10$. Therefore

$$\begin{aligned} T &= 5 \times 10 \\ &= 50 \\ P &= \frac{50 + 10}{2 \times 3\cdot5} \\ &= \frac{60}{7} \\ &= 8\cdot571 \end{aligned}$$

Adopting a standard diametral pitch of 8·4665, *i.e.* a module of 3 mm (p = 0·3711 in.), the centre distance is 3·54 in. approx.

$$\begin{aligned} \text{Pitch circle radius of pinion} &= \frac{10}{2 \times 8\cdot4665} \\ &= \frac{1}{1\cdot6933}\ \text{in.} \end{aligned}$$

$$\begin{aligned} \text{Maximum face width of pinion} &= \frac{2 \times 2}{1\cdot6933} \\ &= 2\cdot36\ \text{in.} \end{aligned}$$

Tangential force per inch of facewidth

$$\begin{aligned} \text{for wear} &= \frac{217 \times 1\cdot6933}{2\cdot36} \\ &= 156\ \text{Lb./in.} \\ \text{for strength} &= \frac{326 \times 1\cdot6933}{2\cdot36} \\ &= 234\ \text{Lb./in.} \end{aligned}$$

Basic surface and bending stress factors required

$$\text{for pinion} \left\{ \begin{aligned} S_{cp} &= \frac{156 \times P^{0\cdot8}}{X_{cp} \times Z} \\ &= \frac{156 \times 5\cdot523}{0\cdot24 \times 1\cdot05} \\ &= 3{,}420 \\ S_{bp} &= \frac{234 \times P}{X_{bp} \times Y_p} \\ &= \frac{234 \times 8\cdot4665}{0\cdot246 \times 0\cdot56} \\ &= 14{,}400 \end{aligned} \right.$$

$$\text{for wheel} \left\{ \begin{aligned} S_{cw} &= \frac{156 \times P^{0\cdot8}}{X_{cw} \times Z} \\ &= \frac{156 \times 5\cdot523}{0\cdot334 \times 1\cdot05} \\ &= 2{,}460 \\ S_{bw} &= \frac{234 \times P}{X_{bw} \times Y_w} \\ &= \frac{234 \times 8\cdot4665}{0\cdot34 \times 0\cdot50} \\ &= 11{,}650 \end{aligned} \right.$$

Carbon steel to B.S.970 EN 32B would be suitable in conjunction with a reduction in facewidth

$$2\cdot36 \times \frac{3{,}420}{9{,}200} = 0\cdot877\ \text{in.}$$

or

$$2\cdot36 \times \frac{14{,}400}{40{,}000} = 0\cdot85\ \text{in.}$$

whichever is the larger, *i.e.* 0·877 in.

Chapter 23

SELECTION OF MATERIALS

A. L. Davies

Introduction

It is probably true to say that a designer always asks too much of the materials with which he has to work. In general, this is a satisfactory state of affairs since it imparts to the materials scientist an ever present incentive to develop improved materials, and also it ensures that the designer has the best material for his purposes available at the time, within the confines of the economics of the exercise.

Many commercial operations are scaled to using the material of minimum cost for doing the job. In some cases a number of materials meet this requirement and then other factors of material utilization come into play, *e.g.* local supplier, long association of company with supplier, ease of fabrication.

For many manufacturers, the ideal material is that which gives excellent service for a given period, and then fails quickly. A material which gives trouble requiring servicing or replacement, but then lasts for a considerable period is less desirable, as users normally prefer an article that is replaced in its entirety at the end of its life, rather than a material which needs constant attention, but lasts for a longer time.

Any article which includes parts assembled and manufactured from a variety of materials is only as useful as its weakest part. Taking as a simple case, a saucepan made of deep drawn aluminium and the handle made from bakelite: in all probability the handle will be the first part to fail or, if the handle has been given extra strength, then the rivets holding it to the saucepan will probably fail first. In this particular case, the saucepan can still be used with a broken handle, but not with a broken rivet.

A more complicated situation arises where many parts are used, such as in a motor car. A motor car, from a materials standpoint, consists of two kinds of components:

(1) Those which are moving and are normally replaced with ease.

(2) Those that remain static, many of which are not replaced with ease.

Thus an automobile may have two or three new engine units during its life, but once the bodywork starts to corrode the end is usually near.

In composite articles, particularly those containing a large number of components, it is extremely difficult to build the final product using materials that deteriorate all at the same speed. Certain obvious discrepancies can be eliminated; for example, no one would dream of making a car body out of stainless steel, as the body would still be intact when the engine design had been superseded. On the other hand, exhaust systems on modern cars could, with advantage, be manufactured from a more heat resistant material than they are at the present time.

At the other end of the scale, articles are made in which the cost of materials is not important, but the performance of materials in service is paramount. Rocket motors must be developed to give a certain thrust, and it is usually essential that this is obtained. Very often this may result in the use of exotic materials, with a high cost.

8

Between the above two situations, there lies a wide field where although cost is not all important, it must be kept within reasonable bounds. The development of aircraft for civil use would normally come into this category, whereas the development of aircraft for military use might well come into the 'money no object' class.

Criteria of Selection

The following criteria would seem to be important in selecting a material for a specific purpose. It is unlikely that all the conditions mentioned would apply to a particular part; indeed, in most cases only one or two will be relevant. However, it is probably true that the more demanding the requirements of the designer, the greater the number of criteria which will be brought in to play.

At the present time, British industry still uses rather *ad hoc* methods of materials selection, but great strides have been made in this field in other countries, particularly in the USA.

Mechanical Properties

A great number of materials need to withstand a certain stress. A simple example would be structural steel. In many cases the strength–weight ratio is important. Although aircraft could otherwise be made from a very large number of materials, in fact the weight of the final machine is so important that the number of materials is limited and at the present time most airframes are made from aluminium and its alloys. In previous years, of course, wood was used a great deal. With the advent of very fast aircraft the heat generated by the passage of the aircraft through the air will become an important factor and it will no longer be possible to use aluminium. The likelihood is that stainless steel will have to be substituted even though this will have an unfavourable effect on the strength–weight ratio.

Sometimes the elastic behaviour of a metal must be considered. In such cases Young's modulus of elasticity is of importance. In general, the value of Young's modulus falls with increase in the melting point of the metal, but magnetic and other phase changes sometimes introduce anomalies, for instance in cobalt.

Other mechanical properties of importance are the plastic and forming properties of the material. No structures remain completely rigid under applied loads and some degree of plasticity is normally required in all metallic components. However, a lamp-post would require less ductility than a bridge member. Thus it is possible to produce a lamp-post out of an easily castable material, *e.g.* pig iron or concrete, whereas the bridge member would have to be produced by some wrought process.

The ability of a material to deform is of vital importance in the selection of materials. Returning to the example of a saucepan, it can be seen that this article may be produced by one of two methods, by casting, or deep drawing from sheet. At one time all saucepans were made of cast iron and were produced in the foundry by melting and sand casting. With cheap labour, the method was reasonably economic but produced an article that corroded readily, had little resistance to impact, and was heavy for housewives to handle. At the present time much kitchen ware is produced from aluminium which is rolled into a sheet and then deep drawn to produce a saucepan which shows great improvement over its cast iron equivalent. It should be mentioned that recently more expensive saucepans produced from stainless steel and/or copper have been produced. This, of course, shows an improvement in appearance, but heat transfer may be questionable.

The temperature at which a material is being used in service is also of great importance. The tensile strength usually increases with lower testing temperatures but the ductility, which is related to the toughness of a material, falls. In body centred cubic metals such as iron, a brittle transition occurs in which there is a marked change in ductility over a small temperature range. This phenomenon is not experienced with face centred cubic metals, but sometimes occurs with metals with a hexagonal lattice structure. The brittle transition is of particular importance in materials used in cryogenic applications.

A very relevant factor is the maintenance of mechanical properties under changing conditions. The most important of these factors are creep and fatigue. Creep is the very slow extension of a material under the continued application of a static stress. Normally it is of importance only at elevated temperatures, but a few metals (*e.g.* lead) have a measurable creep rate at ambient temperatures. Since creep takes place at a very slow rate, information regarding the phenomenon takes a long time to obtain. However, a considerable amount of information has been obtained on the creep properties of materials used in turbines, for example nickel base alloys containing chromium and cobalt.

Fatigue, the failure of a material at a stress well below the ultimate tensile stress, is of importance in any situation where a material is subjected to an alternating stress. Most ferrous materials exhibit an endurance limit, the maximum stress a material is able to withstand no matter how many reversals of stress take place, but non-ferrous materials usually have no such limit, and theoretically would fail at any stress provided the number of reversals of stress was large enough. The presence of a corrosive environment greatly reduces the resistance of a material to fatigue failure. In all cases the endurance limit is drastically lowered, or destroyed completely. In general, fatigue is cured more by good design, for instance the avoidance of sharp re-entrant angles, than by materials development.

Physical Properties

Physical properties such as specific gravity have already been considered on the preceding section. However, other physical properties such as electrical and thermal conductivity, emissivity, or thermal diffusivity are sometimes of importance. Probably the most well-known situation where some of these properties are of importance is in the electrical transmission field. For example, much work is being carried out at the present time to produce dilute alloys of copper with such elements as zirconium and chromium in order to produce materials that have almost the same electrical conductivity as pure copper, allied with an improved tensile strength.

'Resistance' Properties

In the metallurgical field, many materials have to possess an inherent resistance to certain external agents. The most well-known of these are resistances to chemical attack (corrosion), abrasion and temperature. The last named of these has already been dealt with in the paragraph on creep.

Resistance to Chemical Attack

In its broadest application this includes what is loosely called corrosion resistance. Many metals corrode under atmospheric conditions, the most well-known being iron and many of its alloys. Because ferrous materials are used for a very high proportion of articles produced at the present time, corrosion problems are focused on these materials. In steels, corrosion is mitigated by one of two methods *(i)* external protection, and *(ii)* inherent protection.

External protection includes the application of some corrosion resistant material to the surface of the steel. These materials may be another metal (e.*g.* nickel), a polymer or even paint. They may be applied to the steel in a variety of ways ranging from spraying to electroplating.

Inherent protection is afforded by alloying steel with another metal or metals to produce a finished product that in itself is corrosion resistant. The most well-known examples of these types of materials are the stainless irons and steels which are being used in increasing quantities in Great Britain.

Where the corrosion resistance is very severe, for example in the chemical industry, special materials have to be used and alloys of nickel, chromium and cobalt are popular. These materials are extremely costly and are only used where absolutely essential.

Special Properties

Occasionally a material must have a certain special property in order to perform the function for which it has been designated. In many cases, cost is of secondary importance. An example of these special properties are certain electronic configurations which render the material useful in atomic reactors. Niobium and beryllium were initially produced in quantity because they had properties which atomic scientists wished to utilize. Germanium was produced in quantity because it found use in semiconductors.

In all cases, materials with special properties produce heavy development costs and these are not always recovered. It is doubtful whether any money has been made out of beryllium. Conversely, transistors are now paying their way.

Cost, Availability and Ease of Fabrication

Once it has been decided that a certain number of materials are suitable for a particular application (and in most cases there are a number of materials which would be suitable) then the three factors of cost, availability and ease of fabrication become of considerable importance.

It is manifest that some of the newer materials have made inroads into the fields of materials used twenty years ago. An excellent example is the replacement of metallic parts by plastic materials. Before the second world war, a telephone hand set was constructed almost entirely of metal; at the present time only a very small portion of the instrument is made of metallic material. Plastic materials are easy to produce, exhibit a low specific gravity and are non-conducting. Their disadvantages lie in the fact that they are more brittle than metals, have a lower tensile strength and have less heat resistance. However, the improvement in the properties of plastics and the replacement of metallic materials by polymers has by no means finished.

Materials Selection as a Management Technique

It is reasonably common in the USA, though much less common in Britain, to follow a philosophy of product evolution, and to break up materials selection into a number of stages. One example of this technique has been developed by TRAINER and GLASGOW (1965). Materials selection may be broken down into four stages:

(1) Concept formulation,
(2) Feasibility,
(3) Development (final and production design),
(4) Production (or manufacturing).

Concept Formulation

First, a designer develops a generalized system (system image) to represent the general functioning of a device to satisfy a defined, specific need. Next, he visualizes different ways in which the individual functions of the system image can be performed.

When the tentative concept is analysed in terms of applied stresses, fabrication, *etc.*, certain classes of materials can be eliminated. In essence, what the designer really wants to know is whether the concept is seriously limited because needed materials and processes are not available.

A materials limitation may suggest the modification of a tentative concept. On the other hand, it may not be a case of changing the material, but of changing the technology of a material that would otherwise be suitable. The use of the so-called 'Nimonic alloys' for turbine blades in jet engines is a good example. These materials possess the necessary heat resisting properties, but are difficult to fabricate. As a result of research to improve the process technology of these materials, their use is now no problem. Other new techniques such as diffusion and friction bonding, vacuum casting, high energy joining and explosive forming are still only in their infancy and are further examples of improved process techniques making available hitherto unusable materials to the design engineer.

Feasibility

When a promising concept has been selected its feasibility must be determined. Stress analysis work is important at this stage, and the designer must be sure that no factor is overlooked which might place the whole project in jeopardy. After the first detailed examination to determine whether all critical stresses are reasonable, a second examination is needed to determine what types of materials are candidates for the different components. Stress analysis will have to be combined with such factors as corrosion resistance, electrical conductivity, and methods of manufacture as appropriate. When items are critical *(e.g.* bearings, electrical contacts, components in vibration) the more accurately the conditions are known the more specific the materials specialist can be. Tests and experiments will have to be carried out. It is important at this point that the designer works in close collaboration with a materials scientist.

Development

Ideally, the development stage is only concerned with how design functions can best be performed, and not whether they can be performed.

Often the primary objective of the development stage is to maintain a certain level of product performance, while reducing cost to the minimum. Sometimes a particular aspect of performance such as reliability is as important as cost. The probable materials to be used have been determined in the feasibility stage, and the development stage will include a detailed analysis of possible methods of manufacturing components from the probable materials.

Other factors which must be considered are existing facilities, for example types of machines and sales predictions, which might be needed because of the effect of production quantities on production economics. Sometimes it may be advisable to change materials and manufacturing processes as sales rise, though it is desirable that these contingencies should be foreseen and appropriate arrangements made at the outset.

Production

Materials changes or selections made in the production stage often have a profound effect on the success (especially financial) of the product.

One technique that is often applied is known as value analysis, and although the value engineer does not confine himself entirely to the production stage, the technique applied to production analysis has produced astounding economies. Other significant aspects of operation which influence materials modification are tooling, purchasing, and the pilot run. Although work is done in each of these areas during feasibility and development stages, the greater contributions on the part of experts in tooling, purchasing, and production usually occur when a product is actually going into production.

Simply stated, value analysis is an organized method of finding the least expensive way to make a product without compromising quality or reliability. It is a systematic, step by step, method designed to eliminate haphazard cost reduction approaches, and to allow no cost reduction alternative to escape without examination.

A typical approach, popular with large companies, is to have a policy committee and an operations or project committee. The policy committee is composed of management personnel from research, engineering, materials, and processing departments, whereas the operations committee is made up from engineers and scientists from the same departments who actually do the experimental work. Users of value engineering have found it useful to divide the programme into three phases: *(a)* definition of product function; *(b)* creation of alternatives; *(c)* cost comparison and final selection.

The purpose of defining product functions is to find out *exactly* what the part or product is supposed to do and what is required of it.

A study of the alternatives available consists of a search to find out what other designs materials and processes will do the job. Alternatives are suggested regardless of feasibility, and anomalies are eliminated in the cost comparison stage.

In the cost comparison phase each of the alternatives is broken down into individual items which are separately cost analysed and then totalled. In a typical analysis the items are separated into two main groups *(i)* recurring costs, and *(ii)* non-recurring costs. Recurring costs are unit costs that are incurred each time the part is made, non-recurring costs are initial costs.

Although value analysis is probably most important during the production stage, naturally it operates best when integrated into the whole process of materials selection.

Failure Analysis

Another method of materials selection is failure analysis. This method is based on predicting and anticipating all the ways in which a product can fail, and then selecting materials so that failure does not occur. The method can also be extended to specific techniques, such as prevention of fatigue failure (CLAUSER, FABIAN and MOCK, 1965).

Failure analysis can be used in either new product development or in the review and reappraisal of existing products. More problems will exist with new products since little or no experience will have been acquired. The view has been put forward that two types of failure exist *(i)* immediate failure, and *(ii)* delayed failure. Immediate failures cover many obvious sources of breakdown, such as rupture or buckling from direct loading, chemical attack or high temperature softening. Delayed types of failure are more difficult to anticipate and include failure due to stress corrosion, creep, fatigue, or solid state transformations.

The technique of failure analysis involves the study of the environments to which the materials will be subjected, together with the fabrication and manufacturing processes necessary to produce the product. Failure models are constructed in which the failures are described in terms of the causes of failure, *e.g.* functional failure of materials, failure resulting from inability to withstand a particular environment, or failure caused by improper manufacture or processing. Once the failure mechanisms have been determined and analysed, a materials selection procedure can be worked out.

In value analysis the primary goal is minimum cost, whereas in failure analysis the primary goal is reliability.

Existing Products

Although materials selection is most often thought of in the framework of new product development, it is very important in changes in existing products. There are many different reasons for making materials changes in existing products. Some of the most important are:

(1) To solve materials processing problems arising in production.
(2) To reduce production costs.
(3) To reduce basic materials costs.
(4) To make a functional change or improvement.
(5) To improve service performance, including longer life and higher reliability.
(6) To use a lower cost material.
(7) To take advantage of a new material or processing development.

Since the materials selection function cuts across many departments, and engages the attention of many different people, problems of liaison and control may arise, particularly in a large organization. In smaller companies, however, the company metallurgist or chemist often advises on all materials problems, but if in difficulties he can always bring in outside help.

Future Developments

A development which has already commenced is the use of computers as an aid to materials selection. Provided great care is taken in the preparation of information to be fed into the computer, and it is kept up to date, it should be possible to carry out simple materials selection with speed and accuracy.

In complicated situations a computer will be invaluable if it is able to give the sources of information available regarding a particular topic, so that the materials scientist can come rapidly to a considered judgment.

During the coming years, developments in materials will include advances in alloy theory to produce stronger and more resistant alloys, the synthesis of what are at present regarded as natural materials (*e.g.* wood, paper), and the greater use of materials mixtures. It would seem that there is room for development with plastics/paper, plastics/fibre, fibre/metal and plastics/fibre/metal. Metals will be mainly used in the alloy form to give strength, together with toughness, lightness and plasticity, with easy cleaning and non-corrosive finishes. Plastics of much higher strength and heat resistance will be developed and will have a much wider range of uses than at present, particularly in the light engineering industry and most probably in the building industry. Forecasts, such as those of BRECH (1964) provide pointers.

Faced with the ever increasing number of materials available, the materials scientist, in order to achieve the best economic, technological and ethical solution, will have to spend more time in the selection of materials. In the coming years many companies that do not concern themselves with materials selection but adopt the 'what was good enough for Grandpa was good enough for me' attitude, will find that they either have to employ a qualified materials scientist or make wide use of consultants. If this is not done it is likely that they will find themselves in serious difficulties.

Chapter 24

RELIABILITY AND MAINTENANCE

C. T. Corney

Introduction

There is frequently considerable confusion in peoples' minds on the difference in practice between Quality and Reliability; interpretation is not made easier by the fact that 'reliability' is often tacked on, so to speak, to the word 'quality'. Let it be said at once that, without effective quality control, no product will be reliable; on the other hand, the finest quality control, applied to a product whose design is inadequate or which is wrongly applied under service conditions, will not ensure reliability. Thus the simplest definitions, on which this chapter is based, are:

Reliability – The product should look right, work right and should last for the specified life.

Quality Control – A system to ensure that the product, through all stages of manufacture, conforms to the specification.

These definitions are illustrated in *Figure 24.1.*

Although it has already been said that the two are in a sense complementary, until quite recently the emphasis has always been on the 'conformance' side, *i.e.* conforming to the specification and drawing, but with the extension of management control techniques to commercial and manufacturing activities. Special attention should be paid to the methods of achieving reliability, including a system of quality control.

There is a slogan 'quality is everybody's business' and, broadly speaking, so is reliability. But there are certain sections or departments in every firm whose responsibility for reliability is of greater importance than the others – design, research and development engineers, sales and field service people and so on. Therefore inevitably any chapter on this subject tends to portray these spheres of activity in greater detail than the role played by people on the shop floor.

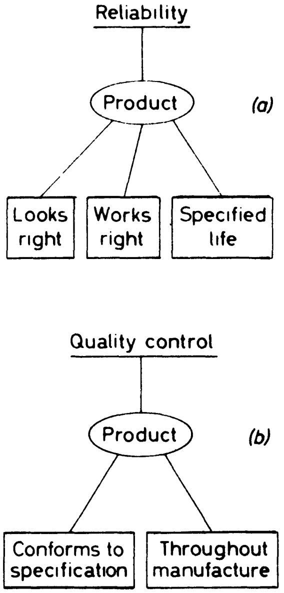


Figure 24.1. Definitions of (a) reliability, (b) quality control

Reliability is so much a first essential in British products that its existence has long been taken for granted. As a result any deficiency in this attribute becomes even more conspicuous in the customer's eyes. The reputation we enjoy today was built on good design practice, and it is therefore appropriate to evaluate the problem of achieving reliability by considering a number of techniques as practical design tools, which are capable of general application.

The financial cost of unreliability is quite staggering, though very often this may not immediately affect the manufacturer. For example, it has been estimated that roughly half the Air Vote (two hundred million pounds) is the annual cost to the RAF of unreliability. On the civilian side, the cost to the Coal Board of maintenance on mining equipment amounts to hundreds of thousands of pounds a year.

In a recent study in the author's own company, the rejection rate in steel castings was as high as 9 per cent; the major cause was condition, with chemical content second. All this work was reject to us and scrap to the supplier and merely represents money thrown down the drain.

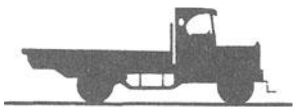
Reliability and the Customer

In the vehicle industry, too, unreliability is a form of waste that can be measured in monetary terms; this waste not only costs the manufacturer money for repair of the component, but in the case of a revenue-earning unit such as a bus, truck or train, it also costs the operator money. A failure affects the attitude of those who hear of it as well as those who suffer it, and once a reputation for reliability is lost it takes many years to regain. The result is customer dissatisfaction with its ensuing effect on sales, which will frequently be a much greater indirect financial loss to the supplier than the direct cost of maintenance or replacement.

A reliable product is one that gives customer satisfaction, but there is no absolute standard of reliability; for example, a component with a mean life of 100,000 miles on a railcar can be regarded as unreliable because of its 'short life', whereas a similar product on a light truck might be perfectly adequate with an identical life. It is the ability to meet a given duty for an acceptable length of time which decides, as far as the user is concerned, whether the product is a good or a bad one.

For many reasons, the reliability required of a product by the customer is increasing; for example expenditure on capital equipment is making very big demands on everybody's pockets, and a purchaser naturally expects that the higher his capital investment the greater the performance and reliability of the product. In the commercial vehicle, equipment has had to meet increasingly severe service requirements. Advanced engine development has resulted in longer periods between engine overhauls, higher annual mileages, higher speeds and heavier loads, frequently under arduous climatic and operating conditions. But while these are factors, they are not the main *cause* of unreliability. Complexity *does* cause unreliability, and modern equipment is becoming increasingly complex. In simple terms, there is more to go wrong and consequently the reliability of each component must be greater than its simple counterpart of some years ago, even if the target is only to maintain the overall reliability of that time.

1928



With 238 critical parts each having a reliability of 99·95 per cent, then overall vehicle reliability would be 90 per cent

1964

With 696 critical parts each having a reliability of 99·95 per cent, then overall vehicle reliability would be 73·75 per cent

Figure 24.2. Effect of increase in complexity of trucks

Figure 24.2 shows the growth in complexity of a road haulage truck over the last thirty years. In order to maintain overall reliability at 90 per cent in 1964, the average reliability of the critical parts had to be raised to 99·985 per cent. But even this is not good enough, for the overall reliability has to be improved in spite of the problem of added complexity.

	Systems reliability (%)				
Individual components reliability(%)	No. of components				
	10	60	100	250	500
99·99	99·9	99·45	99·1	97·5	95·2
99·9	99·0	94·23	90·5	77·5	60·6
99·0	90·4	54·75	36·6	8·1	1·0*
98·0	81·7	29·77	13·3	0*	0*

*Approximate

Figure 24.3. System reliability as influenced by component reliability

Figure 24.3 shows that with 98 per cent component reliability (about right for 100 per cent inspection) a system with sixty such components has a reliability of 30 per cent, and with 100 components 13 per cent. 250 such components give approximately zero reliability. Thus to get system or vehicle reliabilities of 90 per cent, component or product reliability of 99·9 per cent is needed; or put another way, product failure rates of less than one in a thousand.

Thus it can be clearly established that industry has to face an unreliability problem. It costs large sums of money and of the many contributing factors the main one is complexity.

To overcome unreliability the manufacturer must really 'know' his product and be able to prove his 'knowledge' correct. The specification may be satisfactory in that the product functions as required, but for how long will it function? A free maintenance guarantee to replace worn or broken parts is no assurance to the customer who has no desire for 'downtime' on his purchase, whether it be a component or complete unit. It is the manufacturer's duty to sell goods with a known performance and reliability; this will obviously be related to cost, but will give the customer the information on which to decide whether to purchase or not.

If better results are to be achieved, they must first be designed and where possible, fewer parts must be used in products; it is clear that improved reliability is unlikely to be fortuitous (probably the reverse) and it is the design that sets a ceiling to what can be achieved.

The Reliability Programme

The concept of reliability must be present from the first stages of introduction of a product so that it is built in from the start; it can only be added afterwards at the expense of redesign. The importance of the part played by the feedback of information from the user is of paramount importance and is clear from the block diagram shown in *Figure 24.4.*

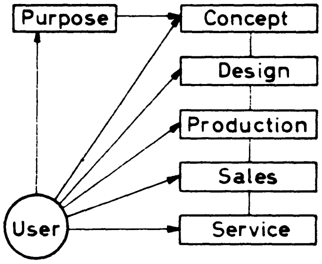


Figure 24.4. Reliability programme showing the importance of feedback of information from the user

It is therefore of value to go through these headings in some detail. (A systematic procedure developed in the USA is that of McCRORY, 1965.)

Knowledge of the Market – What does the Customer Want?

This question seems so obvious that it is sometimes not answered in sufficient detail. With increasing specialization of knowledge

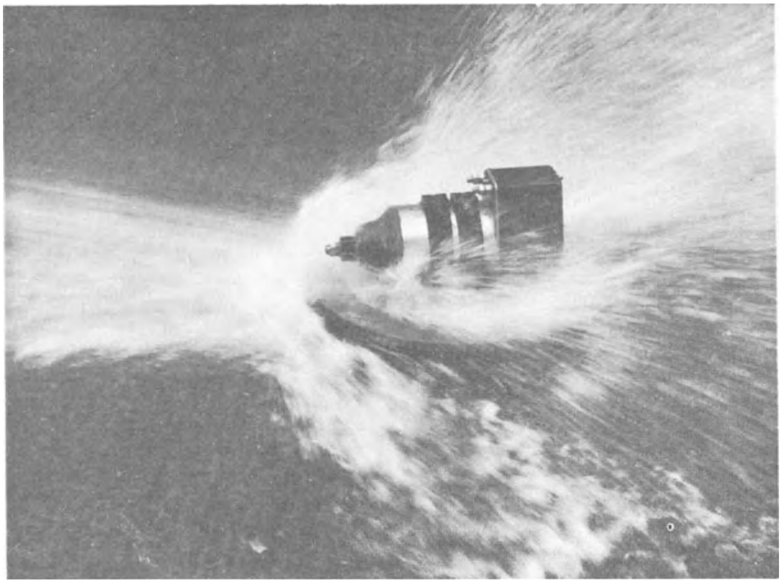


Figure 24.5. Two views of a starter subjected to water from a fire hose, to simulate the effect of wheel splash at 90 m.p.h.

and experience, and with rapid changes taking place, it is necessary to take positive steps to ensure that all who contribute to design detail are aware of the operating conditions of the final product. For example, it may not be realized that the force of a wheel splash on a component of a vehicle on a motorway is almost the same as that from a fire hose (this can go up to 90 m.p.h.); consequently, instead of sitting on a chassis going down the M1, one may conveniently observe the effects of a fire hose *(see Figure 24.5)*. The design specification provides considerable information, but arrangements should be made to obtain first-hand and up-to-date experience and quantitative data on vibration, temperature and other factors involved, including assessment of conditions of use.

Full Product Specification

It is sometimes said, and is frequently true, that too little attention is paid to deciding what reliability is required. Hence the first step when designing a new product, is to prepare a specification which, besides the usual details of external dimensions, will include weight, performance, the range of ambient temperature which must be allowed for, the degree of weather protection required, and so on. It must also include in detail the life requirements under varying operating conditions; it is on this last part of the specification that the actual reliability will greatly depend.

To design for reliability it is essential that all the design staff, not only the conceptive designer, are fully in the picture at this stage. This is where designing for reliability starts and where it is most important.

Translation into Engineering Terms

With a new design, the first conception in specifying what is required – and this really means what the customer requires – is in practice a sales market research function. Normally this conception is unusable as a working document for a designer, and sales engineering must translate the outline into the definite specification terms which a designer can understand and work to. Thus. operating miles or years must be translated into hours or number of operations; environment into temperature, humidity, vibration conditions, *etc.*

Application of Existing Design Life Knowledge

While the provision of a specification is a big step forward, there remains an even greater step which must frequently be taken 'in the dark': designing, on paper, a product with the given reliability but not incorporating such large safety factors that it becomes uneconomical. If the design is largely based on previous experience, then generally that experience can be applied to the new design with appropriate correction factors. If the design is novel then the designer must relate such component information as he can obtain to the overall design reliability and rely to a greater extent on prototype testing.

Published data and previous experience dictate life parameters in some instances, *e.g.* bearing life–load relationships. Rating and pressures, mechanical and electrical wear properties and similar data are available for electrical contacts, brushes, commutators, slip rings, *etc.* Mechanical properties, fatigue lives, ultimate stress and other material properties are normally available. All this information related to product requirements must be immediately available to the designer in an acceptable form.

Published information on the life of branded items may not be in the form required, but one exception is bearing life on which there is a great deal of knowledge; manufacturers have for years expressed life in terms of hours, loads and speeds. However, this data is commonly given for a 10 per cent cumulative failure rate, whereas it is nowadays necessary to operate to much lower component failure rates than this, in order to achieve a product failure rate of a fraction of a per cent within warranty and a satisfactory service life afterwards.

Studies have been carried out in America (see *Figure 24.6*) to determine the source of trouble in equipment supplied by government contractors. While the percentage varied from product to product, studies on different kinds of products showed similar distributions and these figures are probably representative in a large number of cases.

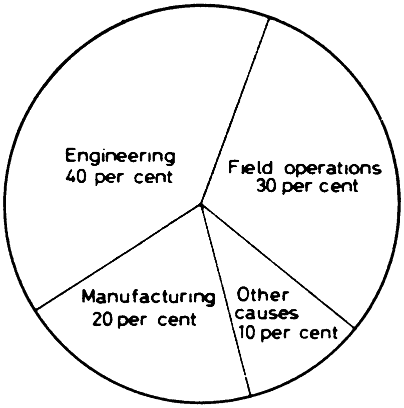


Figure 24.6. Percentage distribution of sources of trouble of a number of different products investigated in America

In the rig testing of prototypes the engineering design is clearly making a major contribution, since at this stage production quantities are not generally available to assess manufacturing conformance – essentially the province of the quality engineer. Rig tests are thus primarily the responsibility of design and development functions, and the type of rig shown in *Figures 24.7* and *24.8* to simulate cycling conditions are in themselves fairly complicated units.

Most new designs or conditions create new problems, and experimental rig facilities must be available to provide the answer. Such testing facilities should come under the control of a reliability engineer who, with the research and development team, also has the chance to assess the type of tests and equipment required in future when the product is in manufacture. Furthermore, a great deal of effort must be put into problems of environmental testing, to ensure that the tests reveal any real weaknesses under the extreme conditions in which the product may have to perform.

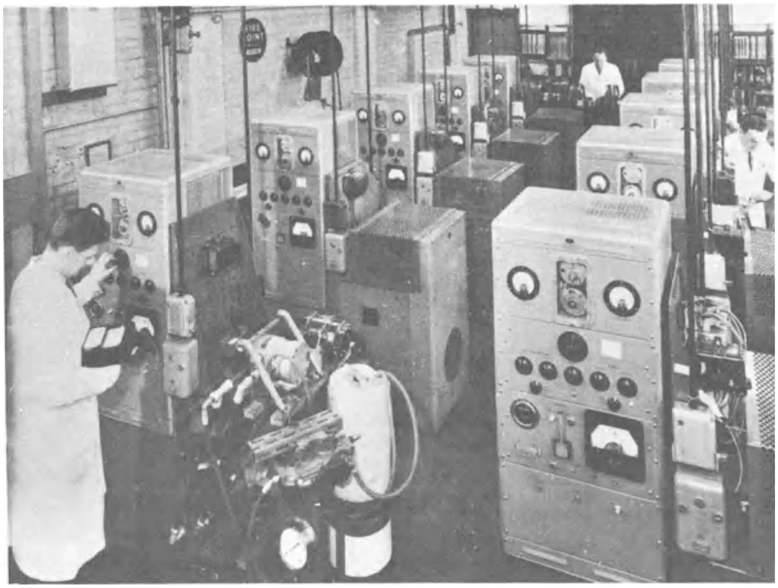


Figure 24.7. Duration test machines for simulating years of service life of a product

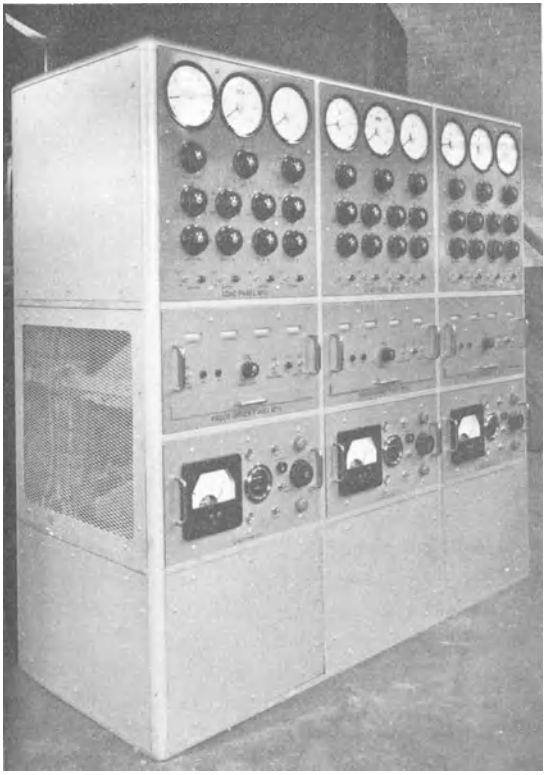


Figure 24.8. Control board for proving tests on CAV product

Control of Manufacturing Techniques and Quality of Bought-out Material

The capability with which the specification can be met in the production phase is a design characteristic. A satisfactory design is one which, besides meeting the performance specification, can also be made economically on the equipment envisaged by the designer. This forms a vital link in the chain of functions contributing to product reliability.

It is sometimes argued that design should not be restricted by the limitations of existing processes and that it is a production engineering responsibility to provide the techniques to achieve design requirements. While there is some justification for this view, the fact remains that if the process is incapable of economically maintaining the parameters required, either these are going to be whittled away by shop floor concessions, or production will be a nightmare of 100 per cent inspection, excess scrap, low operator earnings and the rest.

Some designers say that – like Oliver Twist – they always ask for a little more than they need, as a kind of safety factor; for example a slightly tighter tolerance, a better finish, a tighter performance specification. This is said to cover the grey areas between the black and white of accept or reject. Not only is this attitude an insult to inspection mentality, but it is uneconomical in production, tooling and inspection costs, and cuts away large chunks of allowable tolerance which make statistical quality control possible: and statistical quality control is the handmaiden of reliability. This attitude also reduces the drawing or specification from an inviolate deposition, to the status of a mere guide, subject to interpretation by personnel incompetent to do so, or the subject of interdepartmental wrangles.

It is essential that the drawing (and this includes customer drawings) represent the design requirements and no more.

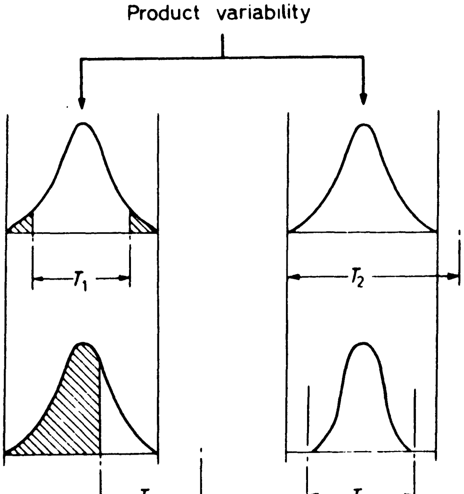


Figure 24.9. Opening out of dimensional tolerance

In stipulating the design requirement for reliable design it is necessary to be aware of and to consider the variation of the process concerned (see *Figure 24.9*). There is no virtue in setting a tolerance T_1 about the mean for an operation whose known performance leaves no room for other variations, even assuming that its variability is within the total tolerance.

Statistics are an essential tool in design when consideration has to be given to cumulative component tolerances. It is surprising how frequently tolerances can be opened out to T_2, far more than was originally supposed, resulting in reduced scrap and yet still allowing reliable assembly. Knowledge of process capability assessment techniques and the interpretion of their results into detailed drawing dimensions should be an integral part of the training of drawing office personnel. It is essential that the design requirements are clearly laid down in the drawing, and that it is understood by everyone that there should be no departure from them unless authorized by senior management.

Full Design and Test Specification

This follows in engineering terms from the previous steps and provides the designer and the quality engineer, at the earliest possible stages, with the basic information to design both the product and the tests and test equipment to be used in design proving and production quality control. The latter are easily relegated to too late in the development stage and can become as much a design problem as the product itself. After designing a prototype to the required specification (at this stage the project has only just begun), a development and proving programme to verify that the product performs under the full range of specified operating conditions must be started.

In a great number of products, such as domestic goods, the service conditions are completely known and understood, enabling design parameters to be specified with certainty, or at least proven by accurate accelerated tests. Testing to failure should always be the goal but, when time does not permit, accurate measurement should be made of wear, *etc.*, which, when related to the length of the test run, will give an indication of product reliability. In a design devised to meet a new requirement, the tests can be made more effective by synthetic reliability testing in which the reliability of detail components is evaluated before they are assembled into the whole complex. *Figure 24.10* shows the specific example of oil seals being subjected to a stringent performance test before assembly into fuel injection pumps.

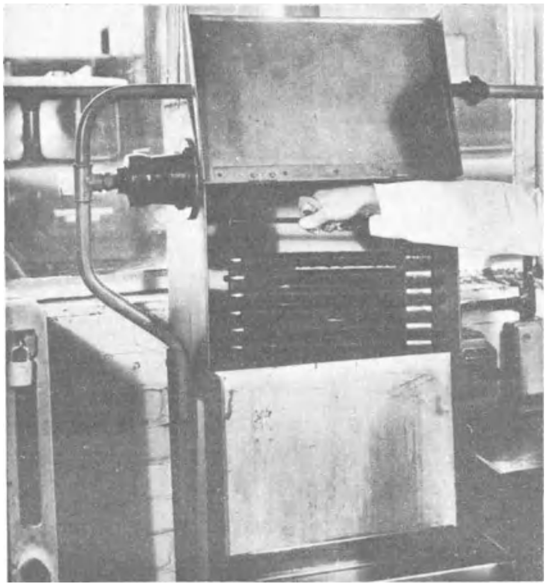


Figure 24.10. Synthetic reliability testing

In general, however, only some aspects of a design can undergo synthetic reliability testing, and it may be uncertain whether all the relevant factors have been recognized and taken into account. In such cases it is prudent, if not clearly essential, to test a proposed design under actual or closely simulated service conditions. Even very simple components can exhibit service problems which can be minimized if they are adequately tested before being released for production and sale.

This takes time and slows down delivery of samples to customers, but it is time well spent.

The properties of products made to a given design vary, often to an extent that matters. This is particularly true of product reliability. In any test, therefore, the test batch must be regarded at best as a random sample of the production which a line is capable of producing. A random sample is, by definition, one arising by chance. Fortunately the effects of chance are calculable – but they are considerable.

The problem of judging a new design by testing a sample batch is similar to that of judging the honesty of a new card school from the first deal. How can it be done? Nothing is certain – except that a hand cannot contain more than thirteen or less than zero spades – but the probabilities of the different possible hands can be calculated. For instance, the chance of a hand containing four spades can be calculated quite straightforwardly by working out the total number of different combinations of cards that can be dealt as a hand, and finding the proportion of these that contain exactly four spades. The chance of being dealt exactly four spades on any given deal is simply this proportion. Writing out all the two million (or so) possible combination of cards would be very difficult, but there are mathematical short cuts which save the labour while keeping the principle the same.

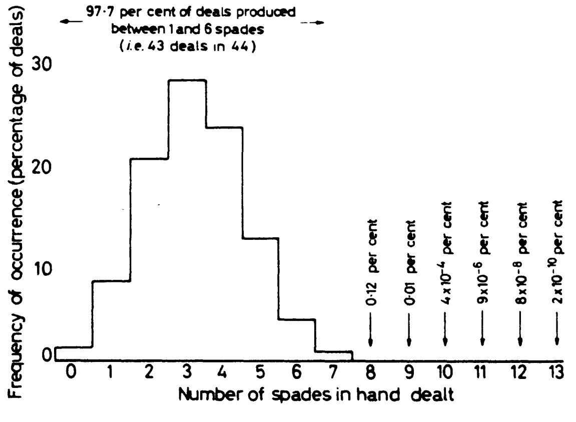


Figure 24.11. Chances of getting various numbers of spades in one hand of cards

The chances of getting the different possible numbers of spades are shown in *Figure 24.11,* from which it can be seen that, although everything from 0 to 13 is possible, values outside the range 1 to 6 are unlikely; they would in fact occur only once in some 44 deals. If on joining a new school, one was dealt a hand containing (say) seven or more spades, one would not be justified in shooting the dealer, but it might be wise to take precautions.

Sample test results must be judged in exactly the same way: namely, in terms of the probability of the actual sample test result arising by chance from a product with a given average reliability; decisions to accept or reject a product must be taken on the basis of reasonable probability rather than certainty about its reliability. This applies to any form of sample testing, whether it is measurement of a continuously variable parameter such as wear, assessment of a product life curve, or simply assessment of the proportion failing at some particular life. In all cases statistical techniques by which the effect of chance may be allowed for are available and should be used; in most cases the results of the necessary calculation are already available in tabulated form. These techniques are not limited to 'normal' distributions and to 'random' failure, although it may sometimes seem so from the literature: in particular, the Weibull distribution allows a wide range of life curve shapes to be dealt with readily. Unless the designer has a comprehensive knowledge of statistics he needs to seek guidance on the interpretation of test results from someone who has. The point to be emphasized is that such interpretation must be done on a statistical basis.

Scale of Testing

Allowance for chance means, in effect, that a margin of error must be allowed on the actual test result. This margin is surprisingly large, or – to put it another way – the scale of testing necessary to make it reasonably narrow can be surprisingly large. The worst circumstance is when the test is limited to determining the proportion of sample failing within a given test period, as frequently happens when progress towards a failure is not measurable and the time available for testing is limited.

Suppose 300 samples are tested on this basis. The best possible result is that no failures occur, and the most stringent acceptance criterion would be to accept the product only if no failures occur. However, it by no means follows that the failure rate would then by zero per cent. It can be shown (by the same kind of argument as for the pack of cards) that if a product with a failure rate of 1 per cent is presented for test, there will be no failure among 300 samples once in twenty such tests: *i.e.* such a test allows a 1 in 20, or 5 per cent chance of accepting a product with a failure rate as high as 1 per cent. If failure rates of the order of 0·1 per cent are hoped for this chance will be unacceptable (*i.e.* 300 samples would be inadequate), and test batches of some thousands of samples may be necessary in order to prove that this order of reliability has been attained.

Such high reliabilities might seem to be special requirements but, as was seen in *Figure 24.3*, to achieve 90 per cent reliability from a system of 100 components the average component reliability must be 99·9 per cent. When one considers the reliability required of the individual components in a complex piece of machinery – particularly components with a number of alternative modes of failure – improvements from quite modest overall reliability levels are, in practice, often found to hinge on improvements of individual fault rates of the order of 0·1 per cent or less.

The multiplicity of items of electrical and diesel fuel injection equipment supplied for a modern motor coach is shown in *Figure 24.12.* Many of these items are themselves relatively complex assemblies, with many components and many different modes of failure. The major

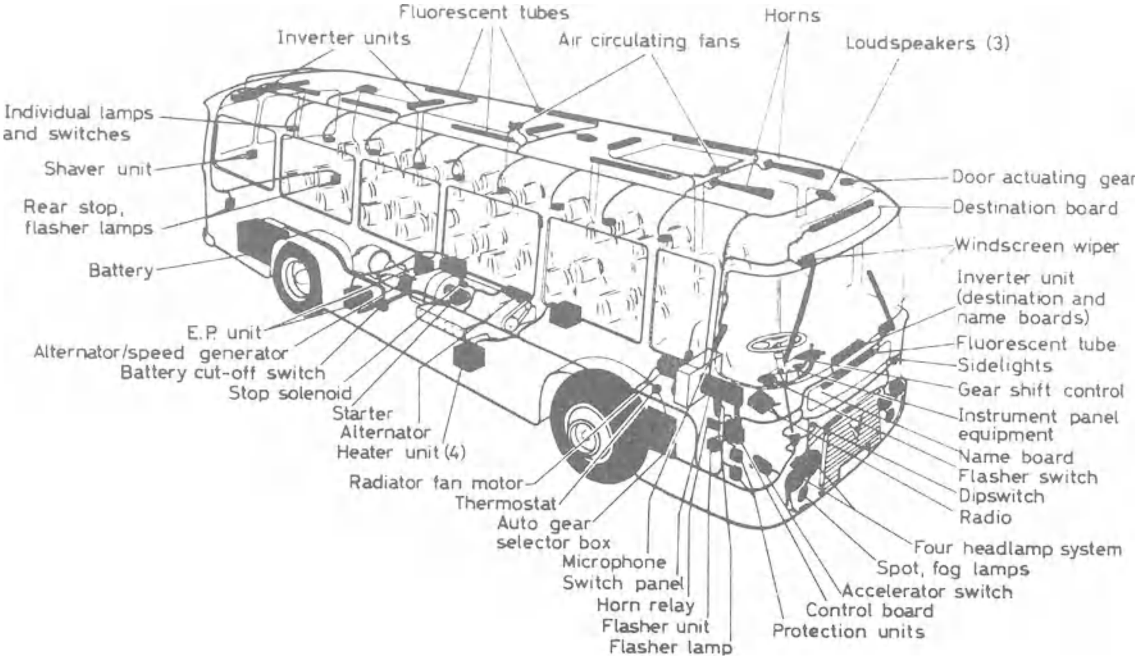


Figure 24.12. The multiplicity of equipment on a modern motor coach

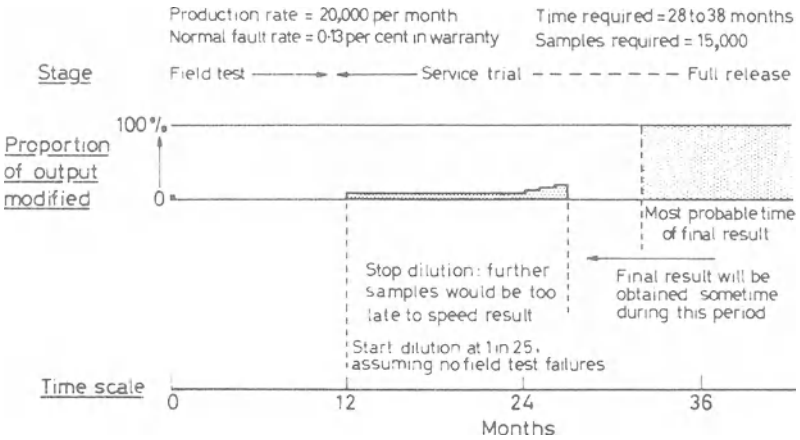


Figure 24.13. Predictable course of service trial of a modification, assuming it not to affect the failure rate

modes of failure found generally show rates of the order of 0·1 per cent during the product warranty period of twelve months. In circumstances such as this, the direct proof of the full required reliability is impossible ahead of design release unless testing is quick and cheap, or there is the time and the opportunity to conduct a substantial service trial.

A Service Trial Procedure

A service trial is particularly possible and desirable in the case of design modification to an established product. The procedure and scale of test required is illustrated by the following example, taken from actual experience.

A particular product suffered a low but persistent fault rate of 0·13 per cent, but the fault was of such critical nature that no substantial increase in its rate could be tolerated. A proposed modification, desirable for other than reliability reasons, was expected not to affect this particular fault rate but, because the mechanism of failure was not completely understood, this could not be guaranteed. It was therefore decided that the modification must be put to statistical test, and could be accepted only if the results allowed a less than 5 per cent chance that it would as much as double the failure rate. The test procedure shown in *Figure 24.13* was adopted, the steps in the procedure being:

(1) All known internal tests and safeguards relating to this fault were applied to the modified design. The modification caused no change to the results, otherwise it would have been abandoned there and then.

(2) One hundred samples were field tested for one year, under controlled conditions. No faults resulted, indicating a less than 5 per cent chance that the true fault rate was as high as 3 per cent.

(3) The modification was introduced as a 1 in 25 dilution of normal production. At this dilution, if the failure rate of the modified product is less than 3 per cent then the overall failure rate would be raised by less than 0·12 per cent (1 in 25, or 4/100ths of 3 per cent) *i.e.* it would be less than doubled, which was the condition stipulated.

(4) The service failures of modified units were compared to those of the normal units, and the strength of the dilution was increased since the results showed this to be safe.

(5) The trial was continued until the service results satisfied the condition stipulated for acceptance. If they had shown that the modification almost certainly worsens the fault rate would have been rejected.

The time-scale and numbers involved in this trial are both too large to be contemplated except in special circumstances. The product was in production at the rate of 20,000 per month; for smaller outputs the trial would take longer.

What are the implications of inability to prove conclusively on a statistical basis? Past experience shows that it is painfully easy to find that expected reliability improvements make the situation worse, due to unforeseen secondary effects which were just not observable on the quantities originally tested. In so far as full proof of reliability is not possible in advance of design release, the other steps in the development process assume added importance. In particular, all reasonable possible steps must be taken to foresee and guard against failure through care in design – particularly where a substantial safety margin can be allowed at no added cost.

In general, customers have some understanding of one's business and will not expect, or pay for, the practically impossible; but, equally they will not forgive failure to take all reasonable precautions.

The Follow-up of Initial Service Results

This is a most rewarding area of reliability activity, since isolated failures examined by design staff are extremely meaningful in interpretation of possible trends, and in instituting immediate remedial action. There may be a tendency to 'explain away' single failures and the statistical significance that these represent is not widely appreciated. It is therefore of great importance that all early failures should be examined in detail and properly explained.

Monitoring Production Quality and Service Reliability

Audit schemes for production 'conformance' may be carried out from sample unit strip-down. These should again be statistically based to satisfy acceptable risk factors. Design has a responsibility, based on user experience, in guiding quality control on those aspects most likely to lead to product unreliability; by concentrating effort in these areas, audit activities can be carried out economically and with maximum effectiveness.

Accelerated tests on complete units will frequently reveal premature failures. These are of value if they indicate a trend in a failure pattern which will be repeated under actual service conditions; otherwise such failures may be red-herrings. If service conditions can be nearly reproduced for monitoring tests, then accelerated testing can give valuable information to design staff ahead of first field results.

Customer Guidance on Application and Maintenance

This is essentially a sales engineering activity governed by the product specification. In the case of vehicle accessories with a great diversity of application, the necessity of a sales engineering manual for each product has become evident, and this makes a suitable check-list for design approval.

The problem of specifying the right product for the right job is necessarily beset by continual competitive pressure, without which everybody would become inefficient, but which in itself can sometimes lead to equipment being used above its reliable rating. Adequate product operation specifications, which clearly show the ratings and conditions for which each product has been designed, are essential in the reliability field. These will enable the user to recognize the correct equipment to fulfil whatever conditions he requires. It is worth bearing in mind that, by paying a little extra at the beginning for a more conservatively rated product, considerable operating economies, through greater reliability, can be achieved.

Guidance from the designer must include the location of the equipment. In the worst cases, this can be so bad that it is almost impossible to carry out normal maintenance so it just does not get done. On the other hand, the product is sometimes located for ease of maintenance but in such an exposed position (see *Figure 24.14*) that water, mud and grit, *etc.* rapidly cause the product to deteriorate, leading to eventual failure. The problem of 'where to put what' is a sticky one, but the design specification is the yardstick against which every suggested installation may be judged.

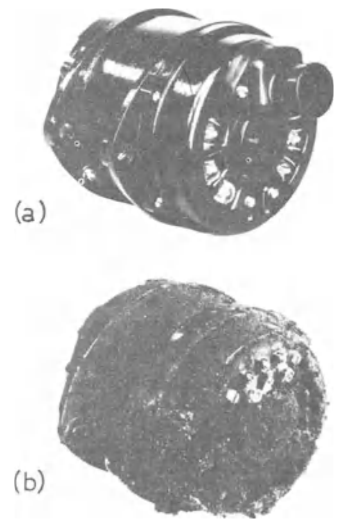


Figure 24.14. A ventilated alternator (a) before, and (b) after field testing in a selected unfavourable mounting position on a vehicle

Feedback of Service Information

Accurate information in service experience, to be used in the development of future designs, completes the design for reliability cycle. It is essential for confirmation of the reliability (or otherwise) of new designs, and for warning the manufacturer of the onset of any new trouble due to changes in quality or in use. It is also important in keeping the designer generally abreast of the market conditions and requirements.

For some manufacturers – particularly those who service their own products *in situ* – the problem of securing adequate information is straightforward, but for others whose products are serviced by dealers, special arrangements to secure information should be made. The author's company represents an intermediate case: service and repair of its products are carried out by its depots and agents, and a twelve months' warranty claim scheme ensures a return flow of data on failures during the first year of service. The information on the claims forms provides a diagnosis of the nature and cause of service troubles and, if it is accurate and is carefully analysed, provides an essential pointer to the matters that should be investigated; it also of course, indicates the reliability during the warranty period. Examination of out-of-warranty failures gives the ultimate life pattern and indicates the progress towards the company's own target for commercial vehicles of a quarter of a million miles without maintenance.

Fairly elaborate analysis is required for two reasons. First, the range of operating conditions of vehicle equipment is wide and failure can depend on factors such as the type of vehicle to which it is fitted, geographical area, month of the year, and length of service, as well as on the quality of production. Second, there are unfortunately variable delays between

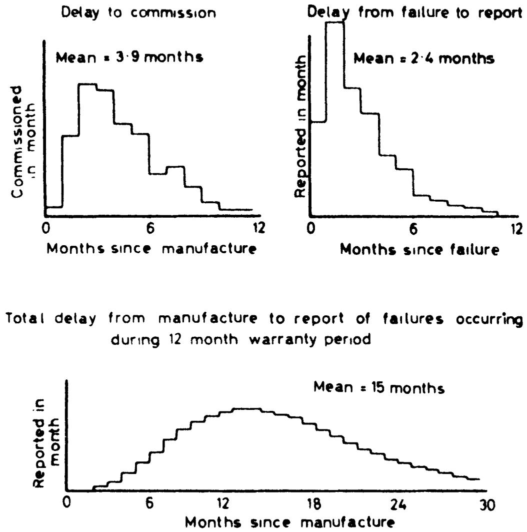


Figure 24.15. Delay distributions for CAV fuel injection pumps in service in Great Britain

failure and the report of the failure, as illustrated in *Figure 24.15*. The result of this is that the warranty claims coming in at any given time cover failures on all vehicles, in all areas, which actually occurred anything up to ten months earlier, and on products *made* anything up to three years earlier. The effect of any sudden change in failure rate for any particular cause, therefore appears only gradually and is difficult to see among the mass of data still coming in from units not affected by the change.

To overcome this and to get the earliest possible, or even reasonably early, warning of a change, routine analysis of the data is necessary with respect to each factor. From this analysis the normal pattern of report, and the variability of this pattern, can be ascertained; significant departure from normal can be recognized; and the rate of failure can be predicted. *Figure 24.16* shows the case of a new design where knowledge of the pattern of delays can allow the failure rate to be predicted with reasonable accuracy from the rate of build-up of the first few returns.

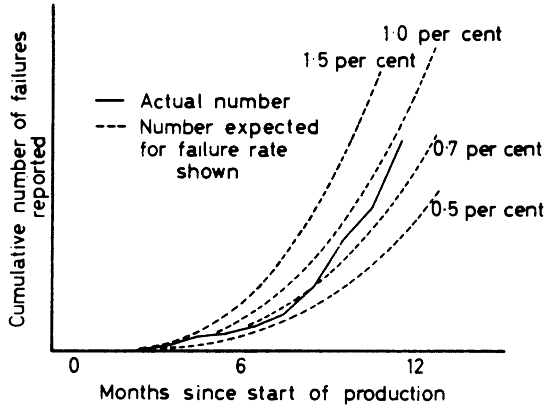


Figure 24.16. *Assessment of failure rate from first few failure reports*

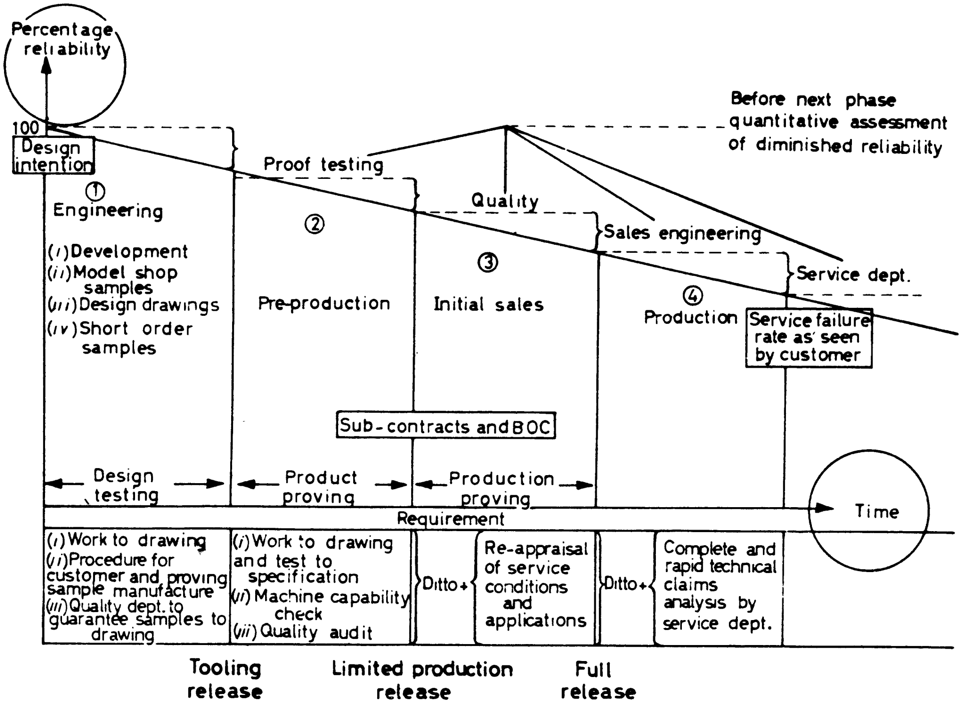


Figure 24.17. *The four phases of reliability achievement*

Analysis in such detail can present formidable clerical problems, and some mechanical aid is almost essential. In the author's company, a digital computer is available and is used for this purpose. At present this is programmed only to sort and tabulate the data in the forms required, but when sufficient data is eventually available on the natural variations in results, it will be possible to programme the computer to analyse the results and to throw up only those features which are likely to be significant.

Co-ordination

It can be seen from *Figure 24.17* that a wide variety of line functions are involved in the reliability programme: service, sales, design, development, buying, production engineering, production, quality control and finally service again. These may be grouped in four phases of reliability achievement:

(1) Engineering – Including design, development detail drawings and sample manufacture responsibility.

(2) Preproduction – Manufacturing quality plays an essential part in ensuring that what is tested is of known quality, to predetermined drawings and specifications. This also provides an opportunity to check process capability.

(3) Initial Sales – Re-appraisal of service conditions and application engineering.

(4) Production – Rapid analysis of early failures using statistical techniques gives upper and lower limits of ultimate failure rate.

The reliability seen by the customer is something less than the 100 per cent envisaged by the concept designer. The extent to which denigration will occur must be estimated and allowed for at the design stage. A quantitative check on the actual diminution should be carried out at each stage by the function concerned, and compared with the design estimate. While this emphasizes the importance of team effort, the designer has a right to expect that the activity will be co-ordinated by someone else, and that the designer will be presented with the information in usable form and will be allowed to approach the design problem, inhibited but not impeded.

Acknowledgment

In presenting this chapter, the author would like to acknowledge the help given by his colleague Mr. D.B. Wedmore, and to thank the Directors of CAV Ltd. for permission to publish the contents.

Chapter 25

DESIGN OF MATERIALS

S. A. Gregory

Introduction

In respect of materials there is a situation which in some ways resembles the problem which has to be faced in other regions of design. Is it better to take a standard material, or to design something specially? Designers generally tend to take materials for granted, as a fixed point.

The arguments which have to be settled partly reinforce this resemblance. A designer or design system engaged in producing a scheme for a batch production job, or a simple one-off job of low value, will avoid introducing uncertainties or expense into the task and will opt for the use of standard materials in so far as these are available. It is at this level that techniques of material selection first come into play. Here the need for exotic materials has stimulated the development of relatively simple techniques.

Design of materials consists in the production of some arrangement of constituents of one or more materials to yield desired properties. Standard materials are those for which the design has been developed and tested, usually with a substantial record of application. The important variables which affect the design of materials are the possible materials and the arrangements which may be made from them; also the specific functional requirements which they have to fulfil.

Material design, which starts from a foundation provided by materials science and the techniques of selection, sees its principal outlets in those design situations where the magnitude of the cash turnover is such as to justify the special design effort and any associated research costs (SMITH, 1965). Such situations will tend to be in flow production jobs, for instance the manufacture of motor cars; in high cost batch production such as the construction of aircraft; in complex one-off manufacture as in the building of chemical plants.

This does not necessarily imply that the material design process will be carried through by the final construction organization. Some manufacturers of materials see the possibility of exploiting their skills and facilities in supplying specially designed materials to fit certain engineering requirements. The production of such materials leads to general availability and the gradual recognition of a new standard material. There is likely to be more 'fall-out' from materials design than from specialized part design because materials are more elementary, having no specific shape.

As might be expected, the design of materials may lead to the design of fabrication processes. Indeed, in many of the practical cases there is an inextricable interrelationship (PEARSON, 1965).

Much of the development of design of materials lies outside the conventional limits of supply of engineering materials, namely metallurgy (ALEXANDER, 1965). Substantial pressures towards the new approach come from thinking about polymeric materials and about composite materials – but this is not to suggest that metallurgy is without interest in the design of materials. Metallurgy provides materials generally with more reproducible characteristics.

Pressures to change the design of materials can come from several sources:

(1) Manufacturers of materials who wish to extend their markets, particularly in competition with other materials of construction, whether traditional or not.

(2) Engineering designers who wish to provide special characteristics to the system they are concerned with, particularly at extreme conditions. These may be associated with high cost batch manufacture, or with complex one-off systems.

(3) Engineering designers who are attempting to bring down product cost or user cost. This is particularly the case with flow production.

In general, the materials giving special characteristics at extreme conditions make up only a small part of the cost of the product; the majority of the total product cost is taken up by the materials of category *(3)* – those associated with searches for reduction in product cost. These are often the materials used in the common types of construction. It is bulk materials of this kind that tend to attract the interest of the manufacturers in their search for large markets.

Where special characteristics are required, the design of the materials is almost inseparable from the design of the systems needing them. Further, because of the tendency of materials manufacturers to avoid small markets (unless the materials have a very high value), their design must almost inevitably gravitate to the systems firm. This may even lead to the development of the production method. Where bulk outlets seem possible the materials manufacturer will take an interest in the design of the material. Unfortunately, there will be an underestimation of the complexity of the needs to be satisfied, arising partly from an absence of direct practical interest in the application of the material, but probably more from the diverse modes of application.

Analysis of Function of Materials

Just as in the better-known areas of design, a practical starting point for the design of materials is adequate specification of function. This may be precise or, more likely in the case of pioneering design, an indication of the preferred limits of a solution. These might come from market investigations in the case of a materials manufacturer, or from preliminary engineering/economic design studies in the case of the system constructor.

As far as can be seen, all engineering functions (excluding aesthetic and other subjective functions) can be classified as either system functions (transformation or transfer), container functions, or support functions. For example, a kinematic system might involve at least a torque requirement and a rubbing contact requirement as system functions. In addition, for all kinds of function, there is a persistence obligation which may be fulfilled in a variety of ways, of which rigidity is one. A container function might require the maintenance of pressure and the prevention of cooling by loss of heat.

A designer attempts to isolate the details of each function so that an attempt may be made to supply what is needed against each detail. The extent to which a design may fulfil the details depends upon the state of the art and the class of solution attempted. Composite materials provide more possibilities than homogeneous materials. Homogeneous materials tend to lead to decisions requiring compromise. In some situations, and in certain industries the design requirements of the materials are taken almost for granted. For example, the heavy electrical industry sees most of its function requirements fulfilled in terms of high conductivity copper and mild steel. The greatest variety probably occurs in materials which execute the containment function, the insulation. In electronics the range of transfer materials is much greater.

In trying to fulfil design requirements, the initial approach will probably be to use a homogeneous material or a material found naturally. Where there are multiple function requirements such materials will lead to compromise solutions.

The response of the materials technologist will be to attempt a redesign of the basic materials. Such redesign, or new design, may have possibilities at the molecular level, at the micro level, and at the macro level.

Materials Design at the Molecular Level

This is largely the field of the polymer specialist. The man who may be seen as the pioneer in this kind of design – Wallace Carothers – called his sphere of activity 'tailoring the long molecule'. His name is remembered through his successful achievement of a new polymer whose use is now widespread in engineering, although it was in the replacement of natural silk in stockings that nylon came to fame.

In this kind of design, the polymer specialist attempts to build up a molecular structure to provide desired properties. He has at his disposal what is potentially a very large number of alternative types of building bricks. From these he has to choose those which are already available, or which promise to be commercially available on terms compatible with the limits suggested by the polymer selling price forecast.

From his chosen bricks he must build up molecules which provide the desired tensile properties, resistance to heat, ability to absorb energy, impermeability to gases and solvents, electrical resistance, *etc.* A great deal of information is now available about the bricks and the ways of articulating them in order to provide the specified properties, although it is difficult to be quite sure what the overall result will be.

The procedure in design is therefore likely to be: sketch on paper the structure or class of structure thought to be most likely to provide results within the given constraints; attempt practical laboratory synthesis; test products; review design in the light of test results; make modifications to structure and synthesize; test; if successful, investigate problems of application and problems of economic manufacture; modify structure as required.

It is through the application of design procedures of this type that there is now available, in addition to nylon, such polymers as polytetrafluoroethylene, the polyester fibres and films (*e.g.* 'Terylene' and 'Melinex' respectively), polyurethanes, organic and inorganic polymers with high thermal resistance, many kinds of synthetic rubber, polyoxymethylene, and the base materials used in a number of modern paints.

Materials designed at the molecular level may themselves be exploited in further designs for materials, either at the micro or macro levels. The possibilities of developing new properties in metals in this category are relatively restricted.

Materials Design at the Micro Level

This class of design is traditionally the preserve of the metallurgist and the ceramist. It is perhaps too positive to term this activity 'design'; during the last century, knowledge has progressed about the way in which microstructure of a material influences its engineering performance – and this has led to control of production processes to provide the structures thought best. However, the last twenty-five years have seen the rise of conscious design in the fields of metallurgy and ceramics: 'alloy design' is now recognized, its name being self-explanatory.

In metals and ceramics, structures are formed which may either be self-composite or hetero-composite at the micro level (HOLLIDAY and MANN, 1964). This is the level of particle size at which surface energy effects are considerable.

Pure metals and solid-solution alloys (or their ceramic analogues) give little ground for manoeuvre, although the obvious manipulation of crystal size may be supplemented by orientation effects and, it is hoped, the *in situ* development of whisker crystals. These additional effects give rise to fabrication difficulties. Where there is more than one basic material the possibility of producing new properties of value increases because the number of degrees of freedom is greater.

Hetero-composites first developed from alloys giving phase separation. Impurities also assisted. The accidental discovery of peculiar modes of behaviour in complex alloys, such as age-hardening in the complex copper-bearing alloys of aluminium, and successive precipitation in the creep-resisting low-cost alloy steels, illuminated the freedom of manoeuvre in some of the more complex systems. Design was possible, but design with a large element of experience and intuition.

Recently there has been something like a return to first principles. Instead of complex alloys being used, attempts are being made to work with single metals and insoluble additions.

Materials Design at the Macro Level

Composites at the macro level give many facilities for design which are missing at the micro level, although they exist to some extent at the molecular level. Macrocomposites provide opportunities for variation in size of components, ratio by volume or mass, shape, spatial relationship, and continuity.

Designers are familiar with many common composites and may have designed some without knowing that they were designing materials. Perhaps the commonest are concrete and reinforced concrete.

The three broad classes of composite are defined in terms of structure: plum-pudding, spaghetti, and sandwich.

Plum-pudding Structures

The plum-pudding structure has variations in terms of size and size range of the disperse phase; in shape; in phase-ratio. The disperse phase need not be solid, and may be gas at any pressure, or liquid at any pressure, provided that there is no continuity between dispersed units. In the most concentrated condition there will be a tendency to interparticle contact. At this extreme it is possible to arrange a composite with the phases reversed, *i.e.* with the disperse phase solid and the continuous phase some other state of matter.

The plum-pudding structure is not normally suited to tensile or torque functions because of the deficiency in continuity of the structure; but the structure is excellent for compressive performance, as in supports such as foundations, provided that rigid 'plums' are used. Rigid porous structures of this class, provided the continuous phase is adequate, lend themselves to thermal containment. Suitable combinations of phases give materials with interesting electrical properties, such as controlled resistance, or suitability for heavy duty contacts. Non-rigid porous structures lend themselves to certain classes of containment or support duties involving mechanical energy absorption.

Spaghetti Structures

Spaghetti structures are built up from fibres or filaments in some continuous phase. The fibres may be randomly oriented or regularly arranged, and may be straight, wiggly, or flexible. Their length distribution may be narrow or broad; the length–diameter ratio influences the composite properties.

With spaghetti structures it is possible to develop some kind of rigidity with very small fibre–continuous phase ratios. This property of the structure is exploited in papers of all sorts, and in most textiles. With high porosity, good thermal insulation and other requirements may be achieved. By specific orientation of the fibres, directional properties may be developed. Under conditions of orientation, it is possible to provide high packing densities of fibre and thus develop valuable tensile properties. Pressure vessels formed by winding suitable fibres at the correct angle on mandrels to a high density, with an impregnation of polymer, now find many critical applications.

Sandwich Structures

Sandwich structures are rich in possibilities and many are commonly exploited. The successive layers in the sandwich may be similar to earlier layers in the sequence, or completely different. The layers may themselves be composed from complex structures. Many common timber products are like this.

Common sandwich composites which are purpose designed by the engineer include furnace walls (for which rational design and optimizing procedures exist) and corrosion-resistant or heat plus corrosion-resistant materials which can take a tensile load. The normal motor car tyre provides an example of a layer structure in which the layers themselves have been specially designed in considerable detail.

Conclusion

The basis of a rational approach to the general design of materials has still to be established. In certain areas such rational design is possible but much more information has to be gathered and specifically directed to the task of aiding design. Up to the present, much investigation has been devoted to the replacement of natural products. A faculty of the technologist is (in von Karman's words) to imagine what does not yet exist. The potentialities for new systems through the invention of new materials is such as to suggest that the time is now come for a systematic exploration of material structures in relation to engineering function and use.

Chapter 26

NEW IDEAS IN THE DRAWING OFFICE

P. McMullen

Introduction

The term 'drawing office' goes back a long way, and until the advent of technical education this was the place where 'drawings were made'; there the whole of the engineering thinking was done – and all too often still is done – by very few people, and in many cases by one person only, out of a drawing office of ten or more. The result was that a draughtsman was purely a 'drawer of lines' and was judged as such. The emphasis was on the drawing and *not* on the design. Also, because the drawing office head would not delegate even the simplest design, he usually became the bottleneck thus encouraging the draughtsmen to over-elaborate just to fill up time; hence over-elaboration became 'established practice'.

The Object of the Drawing Office

The main object of a design office is to clothe technological ideas in hardware, and to provide clear instructions to others as to how to fabricate and erect equipment, buildings, roads, instruments, pipelines, power units *etc.*

Communications

This is the problem of clear communication from one group of people to others. There are many methods, all of which have their weaknesses and advantages – there is no one best way. Clear communication starts in the design office. Most supervisors do not consider carefully what they want to put over to their assistants. They do not put them fully into the picture and assume a knowledge of a lot of background; the instructions are mainly verbal and too long. Surveys have shown that as much as 30 per cent of a man's time is spent in obtaining information.

Information to Designers

The following is an abbreviated list of information that can usually be prepared before a job is started and put in a folder for reference by the designer draughtsman:

(1) Specification sheets giving precise requirements for the piece of equipment to be designed.

(2) Mass balance sheets (these refer to aspects of chemical system functions) giving quantities, sizes, rates of flow, horsepower, *etc.*

(3) Physical properties.

(4) Equipment schedule with leading dimensions.

(5) Standards book for the job. This will include a selection from the D.O. Standards book, plus photocopies of manufacturers' standards suitably marked up.

(6) Target completion date of his piece of design and how this fits in with the programme as shown on the critical path scheme.

Orthographic Projection

The universal basic technique in design offices is the orthographic projection and, despite its many weaknesses, this is likely to remain the principal means of communication from the design office to fabrication and construction. The main shortcoming of orthographic projection is that it tries to represent three-dimensional objects by two-dimensional means. As a result only those people skilled in the art of reading engineering drawings can obtain the proper picture and even they often fail.

Drawings, particularly arrangement drawings, are viewed by very many non-engineers and in most cases they convey virtually nothing. Perspective drawings as frequently produced by architects can be helpful, but they are often deceptive and are expensive to produce.

Simplification of Drawings

Before proceeding to the new ideas in the drawing office, a few ways in which productivity in design can be improved while using orthodox methods are suggested:

(1) Simplify.
(2) Do not make unnecessary views.
(3) Eliminate.
(4) Do not repeat the same detail.
(5) Do not redraw.

A useful leaflet entitled *Functional Drafting* is available, but even this does not go far enough: for example, cross-hatching can easily be eliminated.

Apart from the waste of time in the design office, some other reasons for eliminating drawings are that they have to be *(i)* registered, *(ii)* filed, *(iii)* filmed, *(iv)* printed, *(v)* distributed, and *(vi)* checked.

Checking

This is a time-consuming, non-productive occupation which occupies a large proportion of the most reliable and experienced manpower in a design office. The following questions can be asked:

(1) Is it necessary to check at all?
(2) If it is, to what degree?
(3) Where should the design be checked?
(4) When should the design be checked?
(5) By whom should the design be checked?
(6) What design methods can be used to reduce checking?

In many cases in the author's design office it has been possible to cut out checking altogether and in only a few cases is 100 per cent checking still done. The average time spent in checking is now between 40 and 50 per cent of what was done five to seven years ago.

Models

These can be divided into flow sheet models, arrangement models, and design models showing pipework, electrical installation including lighting, and instruments.

Models are three-dimensional design arrangements of a three-dimensional object. They are readily understood and have many other advantages over conventional drawings, not the least of which is that several people can discuss design points round a model and know that they are understood.

The design is done on the model: it is *not* copied from drawings. Models are expensive but only a quarter to a half the cost of conventional design methods. Speed of design is many times that of conventional methods because people understand the design and, as a result, only a fraction of the usual late changes occur.

Electrical and instrument equipment and runs are shown, as well as pipework; snarl-ups are avoided and planning is better. Since using design models for chemical plant design, the author's design office has met and bettered target dates, and the overall costs have been less.

Preparation of Flow Sheets and Engineering Line Diagrams

The preparation of flow sheets and engineering line diagrams form the basis of chemical plant project design.

There is a basic set of standard symbols which should be used, but these need supplementing by outlines of equipment which make the flow sheets and line diagrams more real. A library of basic equipment outlines, in some cases showing valve arrangements, can be prepared and added to as required. These outlines are photographed on to clear film and can be produced to any desired scale in the numbers required. They are set up on a 'Melinex' film with a squared backing sheet from which a master is printed. A print is taken from the master on to which are drawn the pipelines for the particular service and, in the case of engineering line diagrams, all valves and instruments are shown.

The result of this method has been to reduce the man-hours required to as little as one-eighth of the previous times, not only saving manpower but calendar time in the early stages of design.

Pipework Drawings

Isometric drawings are frequently used nowadays for pipework fabrication. They do give a fair idea of the particular line drawn but usually lack any information of local obstructions and limitations; they are *not* self checking.

By the use of selected basic plant arrangement drawings on Melinex reproducibles, it is possible to take dimensions from the model and show lines to scale in plan and elevation in the standard orthographic projection. A few key dimensions only will be shown. Some of the advantages of this method are:

(1) All engineering contractors are familiar with orthographic projections.

(2) The master general arrangement needs no further checking.

(3) The pipelines are very largely self checking.

(4) Owing to the stability of Melinex, the pipe fabricator can scale all dimensions from the drawing for his shop details.

(5) Speed of communication is improved.

Electrical and Instrument Layout

Using the 'to scale' pipework arrangements produced early in the design programme, master copies can be passed to electrical and instrument departments to add their design for cable runs and instruments layouts.

General Arrangement

By using the cut-out techniques mentioned above, it is sometimes possible to make complete general arrangement drawings. This is particularly applicable to plants where the same equipment is repeated.

Sometimes illustrations and photographs of equipment have been taken, reduced to the required scale, trimmed, and included in a general arrangement.

Modification

One of the advantages of printing on Melinex sheet is that the print is on the reverse side of the sheet and erasures are made on the back, leaving the face side intact.

Where major alterations are required, a print is taken, the parts to be altered are literally cut out with a knife or scissors, a new master printed from this, and the alterations drawn in on the blank spaces.

Notes, Specifications, Tables and Symbols

These are often repeated on a series of drawings. They should be typed with a typewriter on to the film (there is a machine, made in Germany, which can be attached to the drawing board for typing on to drawings). The required number of copies may be printed and stuck on to the basic drawings. Note that this requires one checking only; a machine is used to do a machine's job.

Photography

Generally in industry, photographs are regarded as mainly a medium for recording completed things, but a photograph can also be used as an objective and functional tool that is complementary to design and drawing office work. Photography, used in the broadest sense, is the tool that has helped to improve drawing office methods.

Stereoscopy

Stereo photographs are a more advanced form of visual aid; pairs of pictures are arranged so that, with a suitable viewing instrument, the picture can be seen in three dimensions. The value of stereo pictures is that they permit the observer to separate different planes in the object and to estimate spatial differences, which is often difficult, if not impossible, with single pictures.

Stereo pictures can be presented in several forms. Stereo colour slides that can be examined through hand viewers give the most realistic impression, but only one person at a time can see the picture. Slides can alternatively be projected on to a screen and viewed through polarizing spectacles, so that any number of people can see the picture simultaneously and can point out details to each other.

Another convenient form of presentation is stereoscopic prints in black and white, or in colour, mounted on cards and viewed through a simple magnifying device. Stereo prints can be provided as either individual pairs, or as multiple strips to make a form of line-overlap that presents all aspects of the subject. The overlapping of any pair of prints can be viewed stereoscopically, and, due to the overlap of the area included in each picture, any detail can be viewed from three or four different angles. Enlarged prints of stereo pairs may also be viewed with a similar device in which the eye-base is extended through mirrors.

Photogrammetry

Photogrammetry is a photographic technique that provides a means of measuring precisely, in three dimensions, objects in a picture. Now well-established, with applications in several non-topographical areas, photogrammetry was originally developed for making maps from air survey photographs.

For the engineer who similarly needs 'maps' of designs and illustrations photogrammetry offers a means of obtaining dimensional records with the following advantages:

(1) Photographs are made from a distance without physical contact with the subject.

(2) A complete and permanent record is made in the photograph of all details that can be seen in the camera position.

(3) The visual three-dimensional records are lodged where they are most needed – in the design office.

(4) The photographs need not be analysed until the information is needed – dimensions can be taken from the pictures within a few minutes at any time.

Two photographs of the subject are taken from slightly different viewpoints. The photographs are analysed on a plotting instrument by stereoscopic examination. A mark in the viewing system appears to float in the three-dimensional picture. The position of the floating mark can be moved through the picture and made to follow the outline, or to match the position of any feature that can be seen in the picture.

The plotting system also moves a pencil that draws the plan shapes of the features being probed by the floating mark. The mechanical geometry of the plotter eliminates perspective, therefore the drawing is orthogonal and true to scale.

Photogrammetry of Piping Design Models

One application of photogrammetry in the chemical industry is for making scale drawings of piping designs that have been produced by modelling. The problem here is that whilst the design has been modelled in three dimensions, it must eventually be recorded on paper to give instructions to the piping fabricators and to the erectors of the plant.

The design on the model can be extracted by photogrammetry and drawn more accurately than by any other method. Models are photographed in sections of about twelve inch cubes or larger, according to the building module.

For this work, the plotter is fitted with a second drawing table. This allows both plans and elevation sections to be drawn simultaneously, to provide the information in the required form. The plotted drawings are scaled to match a background drawing that has been prepared from equipment drawings and coordinates, and from structure drawings showing the required sections. These arrangements are the basic drawings from which the plant is constructed and are the most accurate source of information available.

Photogrammetry of Existing Plant

Photogrammetry can also be used for recording and dimensioning existing plants. Here, the problem is that after a plant has been in production, even for only a short time, it has been added to and altered. It is no longer exactly represented by the original design.

From the point of view of designing major modifications, these differences and other details that do not appear on the model or arrangement drawings, can be a major obstacle. Other photographic aids are used as visual references to inform the design office of the present situation, but photogrammetry can often go a stage further, either to bring the design office records up to date, or to provide a means of obtaining exact dimensions in specific areas just when they are needed.

For this work the photographs must naturally be taken from a greater distance than when the subject is a model, and the cameras are transferred from the short base to a longer base bar that is mounted on a surveyor's tripod.

Photodrawing

Photodrawing is potentially the most valuable new drawing office technique that has appeared in recent years. Photodrawings are engineering drawings in perspective, superimposed on a photographic background. They provide an ideal means of communicating instructions for modifications to existing situations. The technique comprises three main stages:

(1) Photograph the existing situation and print on transparent film.

(2) Tape the film print on to the back of a translucent drawing film, and overdraw the engineering information.

(3) Reproduce the combined photograph and drawing on ordinary dyeline or print paper.

The use of photodrawings has several advantages. Both design time and construction time can be substantially reduced. Exact comparisons are difficult to obtain because the same job is seldom done twice using both old and new methods, but results obtained on jobs when photodrawing has been used appear to be outstanding. Compared to times estimated for conventional methods, design office man-hours for modifications to chemical plant are less, at a conservative figure, by 15 to 50 per cent, and workshop effort is less by up to 20 per cent.

The outstanding merits of photodrawing are:

(1) The photograph shows the existing situation up to date, including details and changes not shown on existing drawings. There is therefore no need to check and correct existing drawings before new work can be designed, and repeated visits to site can be eliminated.

(2) Site measurement is reduced to the bare essentials for the job. None is required for the sake of detail otherwise necessary for drawing the background.

(3) Visual representation makes the design problem clear and easier to recognize.

(4) Drawing time is reduced because most of the drawing effort is confined to new work.

(5) Because the presentation is clear, locations and instruments are quickly and precisely understood by the craftsman and site supervision time is reduced.

Photogrids

There are occasions when it is useful to be able to measure dimensions from an ordinary photograph. With care this can often be achieved to an extent sufficient for approximations. A simple case has been taken from a straight-on viewpoint. On the basis of one known dimension the photograph can be printed to a selected scale, or a scale can be drawn to match the scale of the picture. When the subject exists in more than one plane, a dimension must be known and a scale prepared for each plane in which dimensions are required.

When photographs are taken from oblique angles, dimensions can still be obtained. The perspective of the photographic image is in the same central projection as that normally used for drawing in perspective. It is therefore possible to superimpose upon the picture a scale grid drawn in the same perspective as that of the photograph. Such a grid is prepared by applying in reverse the rules for constructing a perspective drawing. The lines of obviously horizontal features in the picture are extended to their respective vanishing points.

Conclusion

There is a whole range of further points to be considered, such as the reasons for using the material Melinex, types of print, sizes of drawing sheets, pencils, lettering, *etc.* – but this would occupy at least a further chapter.

A few years ago, the design rate in the author's office was considered reasonably good, but the rate is now well over twice what it was. Although only a start seems to have been made of tackling the problem of productivity in the design office, it is foreseen that the present rate will again be doubled in the next few years. It should be noted that, with the exception of photogrammetry, *no* expensive equipment is used.

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PART V

MANAGEMENT AND DESIGN

Chapter 27

DESIGN POLICY FORMULATION

B. T. Turner

Introduction

That progressive companies must have an overall design policy for innovation and progressive development goes without saying, but even minor broad policy statements on new products or systems often require courageous decisions to be taken. The consequence of these decisions may very largely determine the survival and prosperity of the enterprises concerned.

KARGER (1960) has stated that 85 per cent of business volume today comes from engineering products which were unknown about ten years ago. Furthermore, there is the ever-increasing tempo of technological change, and the lag between discovery and use is beginning to shorten. Again, fresh ideas for products and systems are tending to be more complex and of greater sophistication; this leads to high research and development costs and complicated testing, *etc.* The result of this quickening pace is that both promoters and investors are finding that new techniques of surveillance, screening and forecasting are essential if any degree of confidence is to be achieved in launching a new design.

Even when such a decision has been taken and communicated to a design group, there still remains a need for clear detail policies regarding any new enterprises or even for modified designs. Hence design policy can be considered under the two headings of company design policy and design group policy.

Company Design Policy

At the company level in a large enterprise there is a need to co-ordinate and guide the various product divisions with regard to their future products. What should they be making now and in five or ten years time? What should be the scope of the product market – is it to be global, continental or national? If a company has to tender for 'turnkey' contracts it is essential that a policy of progressive product improvement, in line with the overall systems requirements, should be pursued. But even for concerns selling individual products, development direction must be specified at the company level in order to ensure a commanding sales position for the future.

There is good reason for believing that some firms would rather run to be second than take the risk involved in being first. This could be not so much a design policy as a way of death; although, if the second is close to the first, it could pay off (Comet *v* Boeing 707). However, a real policy for design which would bring wealth and prosperity to an enterprise demands something more than new ideas and courage alone. Restrictive practices, cartelization, prevention of newcomers entering in competition, maintenance of cost or production, and selling are all factors which mitigate against innovation. If the present production methods and machinery yield a comfortable profit which is assured by rings and cartels, tariffs and quotas, then incentives to redesign or design *de novo* are small or non-existent. Sometimes the cost–benefit factors for introducing a new product through a particular industry do not provide adequate incentives. If such products are in the national interest government action will be required (DUCKWORTH, 1965).

With the ever-increasing need to export, many British firms will have to reformulate their companies' design policies to become more progressive for the nineteen-seventies.

For example, because some large authorities demand a product which is double-foolproof with lush finishes everywhere, designs become uncompetitive for foreign markets. It might pay an enterprise to consider what the true needs of the circumstances really are for foreign as well as home customers. It might pay to design a product so that the extra finesse required can be added to a less stringent basic design, so meeting both markets. Alternatively, separate designs may be required for the home and overseas customers. British standards may be fine for this country when they are eventually issued, but too rigid to allow compatibility with foreign requirements. These factors can lead to over-pernickety design and so hamper exports.

It will be necessary to invest with fresh drive the past industrial dynamic which this country possessed, by applying a scientific approach to the problem of design innovation. Every company in the manufacturing industry requires to create within itself a mechanism which will constantly revivify its designs by applying fresh ideas.

A forward-thinking unit, or product policy committee, must be formed which can take into account past performance of the companies' products and the economic, social and other external influences which will affect the products' future (CORNFORD). Designers should be included in the unit as well as representatives from sales, marketing, research and development, and production departments. Such a committee would be responsible for providing top management with a design brief. This would embrace such factors as an estimate for the validation work necessary to establish technical feasibility of a new product, a survey of the market giving probable sales and profits for the new product, and an estimate of the capital investment required. For this work certain internal and external data must be collected by the forward-looking group.

Data on Past Products

One of the undoubted weaknesses in British industry today is the poor communication feedback from the design, development, manufacture and operation phases through which a product passes. Vital experience and data which is suffused in the whole design-to-use evolution is often lost because it is not recorded and coded so that it can easily be retrieved for future use. Cost–benefit curves should be produced for past products (SITTING, 1963). This is not easy to do since most good engineers tend to move to new pastures as soon as a job has been completed and are reluctant to record mistakes, errors and omissions and are poor at tidying-up operations. But if cost–benefit curves can be done well, they can considerably aid future design policy, for they help to identify strengths and weaknesses.

Data on Customer Requirements

Any forward-thinking unit must have customer contact as well as research contact. It needs to determine, through systematic techniques, the real needs of markets and individual customers (Chase Manhattan Bank Report on European Markets, 1964; HOGMANDER, 1962). The business is determined by satisfying customers' needs, not by producing technical perfection of a product that has become outdated. It is useless to make super rat traps if rat poison is what is needed, or elegant drawing pins if drafting tape is really required. The cycle starts with the customer and ends with the customer; the

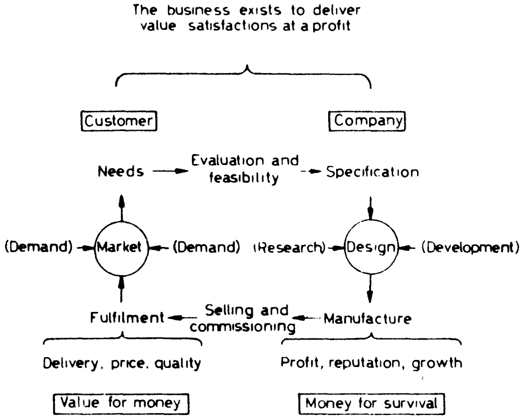


Figure 27.1. Design in the total business cycle

complete business is centred round the customer, not the company. The 'correct' product is one that sells in a competitive market and wins a profit and a reputation for the company concerned. *Figure 27.1* portrays in simple form the complete cycle of operations. In this cycle, information is fed and validation work is carried out by several other departments, such as development, accounts, personnel and other service sections. But the cycle starts and ends with the customer, and design is in the mainstream of translating ideas to hardware for money. The money obtained from the selling price has to be sufficient to yield a profit for survival.

Data on Resources

Not only should the objectives be spelt out in broad terms at company level, but the resources of a company must be known in terms of strengths and weaknesses. The design policy is governed, in part, by building on the strengths and minimizing the weaknesses of any concern. Special expertise and skills, which have been developed over the years, give certain firms superiority over competitors and wherever possible these should be utilized to the full and developed further. Such factors as financial reserves for carrying out extensive development work on a new product must be considered, together with any necessary legal agreements (patents and licensing), factory capacity, existing plant capability and appropriate costs of manufacture, *etc.* Sometimes, when entering a new field, additional skills may have to be added to a firm and a merger or takeover may become necessary.

Maintaining Balance

With the data provided it is necessary to obtain a balance between the market potential and the company potential. For example, the pressure for a new design may come from a research and development department, or from a sales group which has scanned a particular market, or from some other source. The balance is influenced by uncontrolled external factors of supply and demand, but may be controlled to a certain extent by a company supplying a need or creating a demand.

Figure 27.2 shows the necessary balance that is required when looking into the long-term future. The possible market requirement must be balanced against research and development probabilities. Surveillance of the field can be carried out by engineering market research, with careful interpretation (Williams, 1963). This must be done on a continuing basis, since markets can change rapidly. Technical research may be conducted inside the firm concerned or by some outside national body such as NEL, NPL or RAE. Great advantage accrues from designers contacting these government research centres to find out what is going on and what likelihood there is for practical design embodiment of their researches. Quantitative assessment of possible cost–benefit ratios can help to optimize capital expenditure, *etc.*

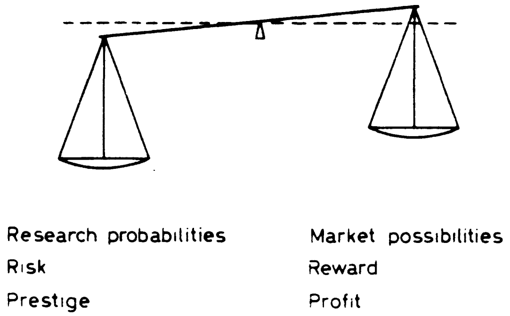
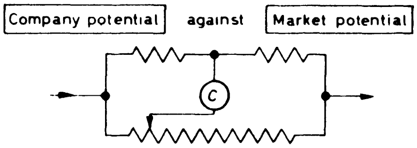


Figure 27.2. Dependence of long-term policy upon balancing commercial possibilities against research possibilities

For short-term policy considerations, it may be necessary to create markets. There are many relevant factors which have to be considered and some of these are listed in *Figure 27.3.* Design policy is influenced by most of these factors to a greater or lesser degree. For example, advertising is essential to increase sales of not only soap powders but also nut-and-bolt engineering products. Ultimately, it will not be the country that can produce most that will win the battle for world markets, but the country that can sell its products most efficiently – and advertising is necessary to boost sales. If sales increase, it may pay to design special tooling to cope with the increased demand; if direct selling is used, servicing will be at the customers site, and consequently design policy will be affected.

Political activities may include government contracts, perhaps imposed for defence reasons, and making use of government surveys, *etc.* Short-term boosts may require design policy changes, which can include collaboration with competitors or price cutting and dumping. Taking a licence will also require careful design handling, for often drawings have to be anglicized and redesign may be necessary to use existing production facilities. Product life-cycles will influence design considerably as obsolescence is considered *vis-a-vis* longevity of life.



Company control *C* is achieved by either creating a market or satisfying a market

Creating a market by:	Satisfying a market by:
(1) Sales activities	(1) Increasing production
(2) Political activities	(2) Decreasing production
(3) Short-term boosts	(3) Giving licences for manufacture
(4) Taking licences	(4) Altering channels of distribution
(5) Altering product life-cycles	(5) Maintaining standardization

Figure 27.3. Dependence of short-term policy upon balancing potentials

Changes in market conditions may require action to satisfy a market, and this can be done in a number of ways. Some of these are listed in *Figure 27.3*, and it can be seen that these also demand design effort of one kind or another. For instance, increased production may be achieved by additional capital expenditure or by sub-contracting, both of which require extensive design liaison; decreased production may require diversification or closing down of certain lines. Yet another way of satisfying a market might be to give licences for manufacturing and to alter the channels of distribution. Rationalization of products may also help as unprofitable lines are cut out and profitable ones become standardized.

Possibilities	Danger points
(1) Increasing the sales price	Market may decline
(2) Increasing the market by reducing profit per unit	Too low a profit margin
(3) Reducing total costs and so reducing sales price	Quality may decline and capital may be necessary

Figure 27.4. Profit increase in a static market situation

In considering all these factors, the ability to achieve a profit is of paramount importance. A profit increase with a static situation may also require attention and the possible ways of achieving this, with the inherent danger points, are listed in *Figure 27.4.* For any changes made, the break-even point should be determined.

When all these factors have been carefully considered in the light of the strength of the concern, a company policy for design can be formulated. Such a policy must ensure that any projected products meet the market at the right time, hence proper planning to phase in a new product and drop an old one are important. It must be remembered that the problems associated with discontinuing a product are as

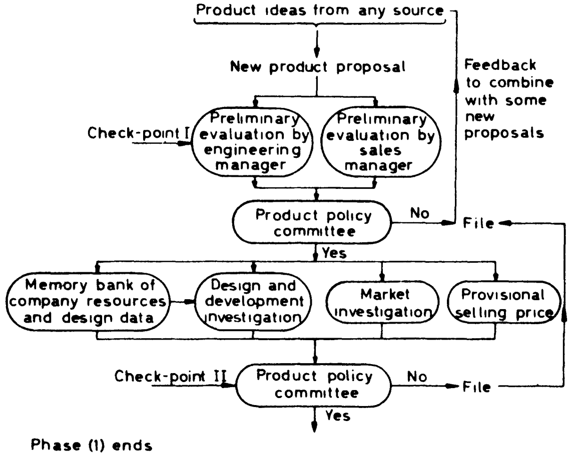


Figure 27.5 Phase (1) in the introduction of a new product

great, and sometimes greater, than introducing a new one.

Phase *(1)* of the operation of introducing a new project is now completed, and the discrete steps in formulating the company design policy are set out diagrammatically in *Figure 27.5.* It should be noted that, before design and any development are authorized, a considerable amount of data collection, collation and sifting has been carried out. The product policy committee has considered and weighed carefully many factors given them by specialists. Only by doing this, can a correct company design policy be formulated.

Design Group Policy

A policy is not a directive or a command, but a guide. The company design policy clarifies the viewpoints of top management concerning direction and provides a pattern or framework within which the design group may operate. Such a guide establishes latitude and longitude of product design decisions, anticipating future trends and conditions; but detailed design policies must be made at the design group level. It is as well to have certain policies written out, so that all members of the group clearly understand what is demanded of them and what are the product or system objectives.

When considering this subject without reference to a specific product, it is not possible to be too specific about design policy proposals, but some of the most important common aspects are given here.

Of course, every product can be looked upon as an organism with a definite life-cycle. The hard effort required to bring a new product to birth from abstract ideas needs an expensive launching period and, like a child, it may require considerable support before it is fully developed and self supporting. In order that the growth phase may be reached as soon as possible, the following factors are considered important.

Simplicity

In general, the simplest design that meets the specification should be used. The policy should always be to reduce the number of parts and make the product containment as small as possible. The technique of value engineering can be applied to this aspect with great effect if it is used in the design process. For some engineering work, the use of notational models can be a valuable aid to achieving the required simplicity.

Cost and Weight Control

Targets for cost and weight should be set as a matter of policy, and should be continuously monitored. For example, with heavy electrical machines the effective use of active material – copper and coreplate – cannot be reduced if performance guarantees are to be met. The required amount of copper must be present, but the other components may be controlled by weight and cost factors so that good utilization of material for fabricated parts is achieved. On certain stator frames it has been shown that material wastage can be as high as three times the net weight. Here again all the company's past designs should be analysed so that realistic figures can be set as targets. A typical example for a generator is given in *Table 27.1.* Both cost and weight monitoring on large projects can be greatly assisted by the use of computers.

Standard Parts, Components or Items

Standardization should be part of every design group policy. Wherever possible, a tried and proven designed part or component should be used. This applies for systems designs as well as product designs. Non-standard parts have high production costs, high inventory and work in progress costs, as well as difficulties in planning and inspection. A typical example showing the relative costs for a standard machine and a special machine for a small industrial motor can be seen in *Figure 27.6.* Control of the use of non-standard items is probably best done by a committee approach where full justification has to be given.

Drawings of proven designs need to be coded, not by piece numbers, but by shape and size, so that designers can easily retrieve past designed components, parts, *etc.*, to use in the new products. Similarly preferred sizes of raw material should be used in new designs,

Table 27.1. Material, Labour and Factory Overhead as percentage of Basic Product Cost

		Material	Labour	Factory overhead	Total	
Field system	Frame	5·46	0·44	0·95	6·85	
	Main pole punchings and assembly	3·08	0·44	0·95	4·47	
	Main field coils	2·69	0·22	0·46	3·37	
	Compole punchings and assembly	0·90	0·27	0·60	1·77	
	Compole coils	1·56	0·40	0·84	2·80	
	Compensating winding	3·30	0·64	1·40	5·34	
	Field connection	0·55	0·19	0·42	1·16	25·76
Armature	Shaft	6·95	0·51	1·11	8·57	
	Armature hub	0·81	0·40	0·86	2·07	
	Armature core and endplates	4·32	0·75	1·67	6·74	
	Armature winding equalizers and assembly	3·84	3·25	7·08	14·17	
	Half coupling	1·79	0·25	0·55	2·59	34·14
Commutator	Commutator hub and baffle	2·36	0·16	0·34	2·86	
	End rings	3·42	0·12	0·28	3·82	
	Commutator bars and risers	6·10	1·52	3·30	10·92	
	Commutator assembly	0·43	1·15	2·52	4·10	21·70
Brushgear	Brushgear	2·08	0·99	2·14	5·21	5·21
Covers	Endbells	0·92	0·91	1·99	3·82	3·82
Pedestals	Pedestals and bush	1·87	0·39	0·84	3·10	3·10
Miscellaneous	General erection, painting, etc.	0·29	1·85	4·13	6·27	6·27
Total		52·72	14·85	32·43	100·00	100·00

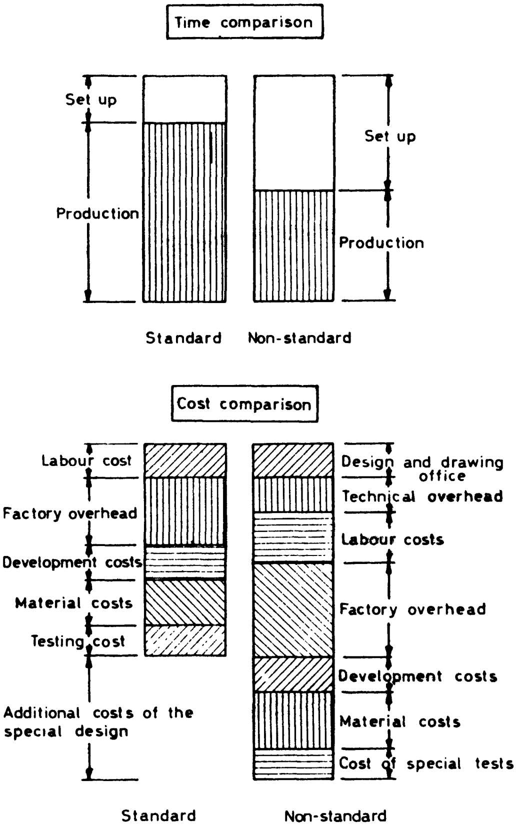


Figure 27.6. Relative costs of a standard design and a one-off design

since this allows flexibility of purchasing and cost reduction by bulk buying.

For some products, careful considerations should be given to the setting up of the correct standards so that overlapping is avoided. Here, preferred numbers and geometric series of sizes should be used. Where some form of variety is required for specials, the design should be such that these can be introduced to a standard framework on the last 20 per cent of the final assembly.

Allowance for Flexibility (uprating, etc.)

With an entirely new design on such products as prime movers, a group design policy should initially be laid down about possible requirements for growth of performance. If the initial design aims at too high efficiency, it can lead to an inflexible product. It may sometimes pay to have additional strength added to scantlings in order to allow for higher compression ratios later on. In some cases this conflicts with the cost and weight control, and necessary reconciliations have to be made.

Insurance that Designs can be Maintained, Operated and Cleaned Easily, and are Pleasant to View

Cost effectiveness of any technical product does not only depend upon pounds per output (£/kW or h.p., *etc.*), but also upon cost of servicing and installation. The estimated outage cost of a 500 MW steam turbine for one month is about £1 million. If the duration of such an outage is largely caused by the difficulty of dismantling to install a new part or component the design must be considered inadequate. A servicing policy must be laid down for the product. Will replacement be by assemblies or components? What holding of spares will be at site, at base or elsewhere? What is to be their shelf life? What is to be the warranty period for the product? Will the warranty be tied to regular servicing conditions by approved dealers or agents? Operation of certain engineering products too often assume a superhuman dexterity: control levers are difficult to operate and meters are placed in impossible positions. Such ergonomic factors are vital and basic data sheets on space requirements and optimum movements for drivers, pilots and operators must be issued to the design team (PILDITCH, 1964). Cleaning is also important, and aesthetics are becoming more and more important even for capital goods. A design based on a sound policy which took these factors into account is shown in *Figures 27.7* and *27.8*.

Manpower Considerations

Every design group policy must consider the manpower available to tackle the new job, and whether the men are trained for the work? More often than not, little provision is made for training or retraining. Members of the forward-thinking unit must give talks to the group so that the complete background knowledge of the proposed project is understood.

As new tools and techniques become available they should be committed to software for programme-learning. Teaching machines may be used to teach designer/draughtsmen the importance of such aspects as statistical tolerancing, reliability factors and bearing design data.

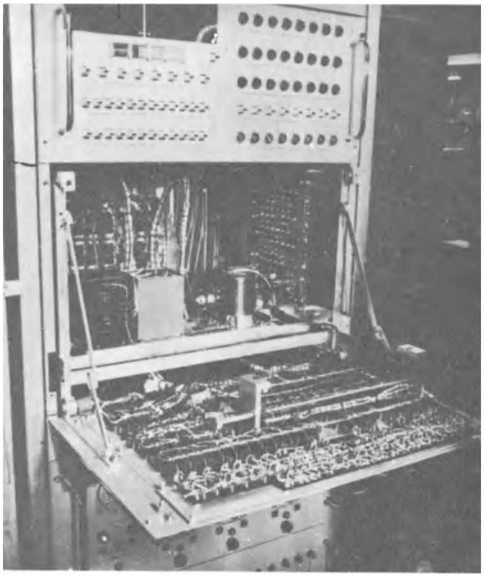


Figure 27.7. Engineer's control cabinet in open position for servicing

Figure 27.8. Testing and replacing a logic circuit

At the other end of the manpower scale, it is necessary to have operator-training underway well before delivery. Initially, this will probably have to be done at the designers works. Models or analogues may be required to familiarize operators with control procedures. Certainly handbooks will need preparing, and it should be a design policy to issue these when delivery of the product is taken. For many engineering products these are either forgotten or are produced very late.

Use of the Best Method to Communicate Design Intent

While the drawing has been accepted as the universal language for communicating a design, too often a two-dimensional presentation has been used. A good design group policy would include the necessity of using representational as well as orthographic drawings.

Wiring diagrams may be replaced by computer print-outs, piping diagrams by models and photographs, testing schedules by tape recorders, and so on.

Production Considerations

No design group policy can afford to neglect new procedures and present process capabilities. Designers must know where and how their creations are to be made. It may be profitable to set up a 'make or buy' committee which consists of production, purchasing and design representatives. If items are bought outside the company, then careful specifications are necessary, and a project quality survey of the sub-contractors facilities should be made before a contract is placed.

Setting up of Adequate Check-points in the Organization

In order to control the process of producing the correct quality hardware, appraisal check-points must be provided and these can best be illustrated by referring to the flow charts given in *Figures 27.9, 27.10* and *27.11.* If these are read in conjunction with *Figure 27.5,* it will be seen that altogether there are eight distinctive check-points in the translation process from a feasibility design study to the issuing of manufacturing instructions. This is for the

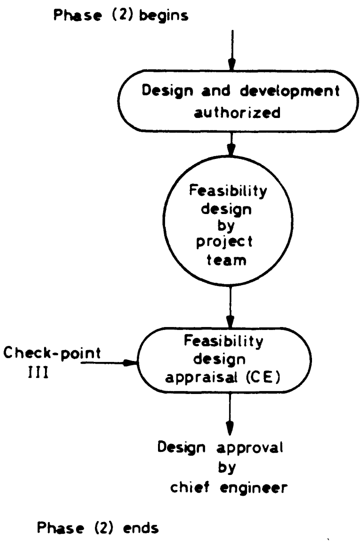


Figure 27.9. Phase (2) in the introduction of a new product

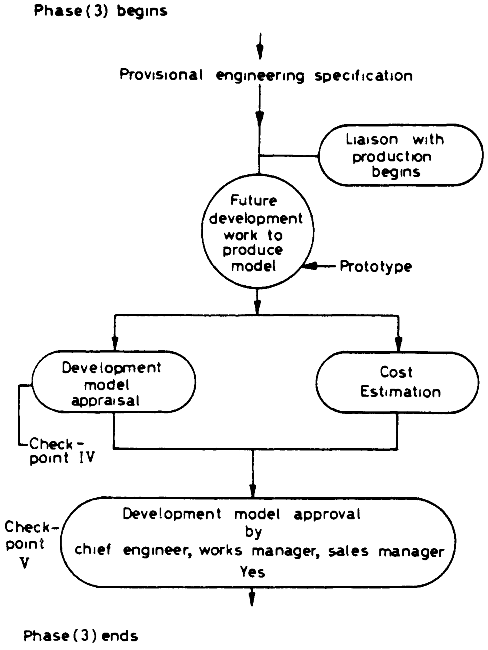


Figure 27.10. Phase (3) in the introduction of a new product

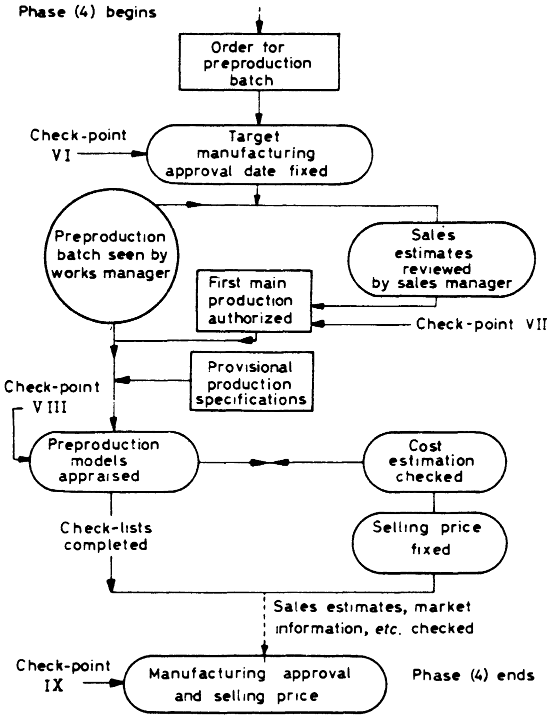


Figure 27.11. Phase (4) in the introduction of a new product

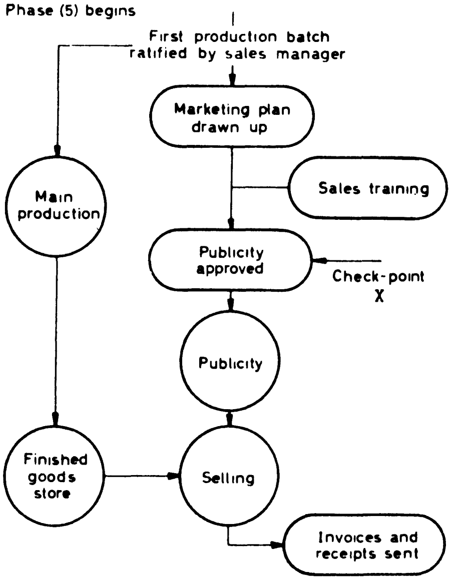


Figure 27.12. Phase (5) in the introduction of a new product

introduction of a batched or flow-production product.

Of course, these may vary from company to company, according to the nature of the business undertaken, but it should be a design policy to fix where and when these checks are to be taken. Only by using such 'gates' can errors and omissions be avoided and a selling, profit-making product be produced. It should be added that, in line with the production, there must be a proper marketing plan supported by adequate publicity and this is indicated in *Figure 27.12*. Many good engineering projects have failed either because they have been poorly handled or have been launched at the wrong time. To combat the former there must be a publicity promotion programme, and to avoid the latter, adequate planning throughout the design and manufacturing processes must be set up as a design policy.

Conclusion

In this age of rising expectations, customers for capital and consumer goods are becoming more discerning. They are better educated, more sophisticated and more affluent. Design has to be tailored to suit this new atmosphere. The accelerating pace of innovation will continue, and consequently companies will have to consider even more carefully their choice of products. The scientific method must be applied not only to confirm technical feasibilities, but also to market considerations and financial aspects.

Company policy must lay down the broad direction for design groups to follow, but the groups themselves must pay attention to many detail policy matters, narrowing the framework of operation so that optimum use of the company's resources takes place profitably to satisfy an identified need.

This chapter specifies some of the requirements for successful design policy formulation, but it does not claim to be exhaustive. A possible flow chart of the operation of introducing a new product has been suggested. This emphasizes the need for providing adequate check-points throughout the complete operation of converting ideas to money.

Acknowledgment

I wish to thank the English Electric Company for permission to publish this chapter.

Chapter 28

INNOVATIVE DESIGN AS A POLICY FUNCTION

R. Davis

Introduction

This chapter concerns the optimization of conditions to encourage improvements in design for manipulative machinery. It attempts to indicate some of the reasons why standards of design in such work are not good enough and calls attention to successes in other fields such as aircraft design, nuclear plants, and the automobile industry, where design is regarded as of sufficient importance to be the immediate concern of directors.

In the FEILDEN report (1963) it is suggested that the designer should be given increased status and reward, but no suggestion is made as to how to do this. Such gains are frequently the result of self-advertising and political teamwork. Good designers are often not interested in applying themselves this way and become bitter and disaffected on realizing their losses.

With the expansion of organizations utilizing technology to make profit, control moves from the technologist to the financier, organizer, or accountant. These people make efforts to select technologists but in recent years, perhaps due to lack of self-confidence, they have relied on the technologist to sell himself to them, and then have delegated, with many restrictions, the work of maintaining progress to the successful applicant. These successful applicants are often organization men who have more in common with the people who accept them than they have with the typical technical creator. They often depend on the prestige use of qualifications and the selling of second-hand schemes rather than on the use of technology as a creative tool.

This trend is not confined to mechanical engineering, but is common in many industries depending on technology. It atrophies creativity by putting the control of creative facilities in the wrong hands and can only be rectified by directors resuming immediate responsibility for technical progress, accepting a feedback from creators, and using this feedback as a factor in setting policy. This type of change would do much to rectify the status situation for such creators as innovative designers.

Range of Design Functions

The term design covers many activities, ranging from detailing to innovative design, and may even include some branches of research. *Table 28.1* shows in simplified form how these activities interlock with other activities in an engineering firm. In practice they have all been lumped together because they all depend on the use of a drawing board and eventually lead to a detail drawing, despite the fact that they depend on skills as diverse as academic, craft, or creative skill. The table shows the range of work which is concerned with immediate profit, and should come under day-to-day management, and the range which involves policy and should be the concern of directors. Such a division would enable the director to profit in setting policy, and the creator to improve his performance by knowing the director's problems. To bring innovative design under a director would shorten the lines of communication concerning hidden problems and potential solutions. These lines are often weak and faulty and are among the weakest links in modern industry.

Figure 28.1 shows a director's possible approach to evaluating design staff. This could develop into meetings called by the director for his proved and potentially creative staff, either as a group or individually, at which they would learn of his problems, and they could contact him first by memorandum and then personally in order to put forward potential developments. He would also learn of their difficulties in acquiring non-engineering knowledge essential to designing, be able to replace committees with essential consultation, and probably achieve much more with well-understood traditional engineering techniques before making recourse to the invaluable but expensive techniques of modern technology (DAVIS, 1964).

These group meetings between a perceptive director and his staff could do much to break down the barriers that have grown between

Table 28.1. Interaction of Design and Other Activities

Design – levels, factors, controls, skills, associated activities								
Type of design	Example	Origin of need	Character of work	Objective	General need for change	Change in control need	Change in skill need	
Detail	Shop drawing	Production	Almost a *craft* activity needing production experience. Answerable to production manager	Communication records, future service, fixing detail and fixing cost of manufacture	Complex and costly systems need revision; time wasted on prestige appearance of drawings; more practical manufacturing know-how needed	Leaner management; more cost consciousness on both methods and products; better incentives to draughtsmen	More shop experience on production and inspection	Craft
Routine	Structures of different size; new models of existing machines for different sized products	Customer and sales	Routine craft work on basis of technology and experience. Answerable to general management	Realization of requirements on service and cost, to meet competition	More attention to users needs; better instrumentation, appearance, servicing and mechanization	More critical appraisal of product and completeness of the design	Field experience needed; more perseverence to complete the design	
Improving	Speed-up of instruments, mechanization	Sales, competition and forward-thinking by directors	Partly routine using engineering experience, technology, some creativity and experience of use. Free to reach director to over-ride manager	Progress, quality, and security by meeting competition	Determination not to fall behind awareness of progress	More technical directors with real power; more knowledge of users needs; demand for improvement; search for ability and innovative ideas	More knowledge of users needs; more engineering knowledge; insight and courage	Creative
Innovative	Completely new project or techniques	Director's foresight; director's acceptance of new ideas from creative staff or users	Creative, based on experience and technology	Desire for progress, high profit through monopoly, security, and good image	Better communications between creators and authority; need for national awareness of importance of industrial prestige; more awareness of importance of breadth of thought and attention to detail	Allocation of money to unpredictable innovations; the search for innovations and innovators; resistance to the build-up of high parasitic costs on budgets, estimates, management and feasibility insight	Access to more information on users and modern techniques; consultation with other skills; ability to contact and communicate to directors; training in creativity and observation	
Development research	Aquisition of data by mock-ups; use of advanced transducers on production or pilot plants; mathematics; computers; new scientific discoveries	Designer, director and user	Advanced instrumentation; mathematical skills to solve complex problems, consultant. Answerable to director and designer	Accurate information to aid creative thought	Limitation of control of facilities and programmes by non-creative people, control being granted on strength of exam successes; better efforts to feed competent but non-creative technologists with work programmes of importance and needing their knowledge	Appreciation of worth and the limitations of non-creative technologists; understanding of the needs of creative designers	More practical training; more training in use of imagination and observation; less abstruse communication technique	Academic

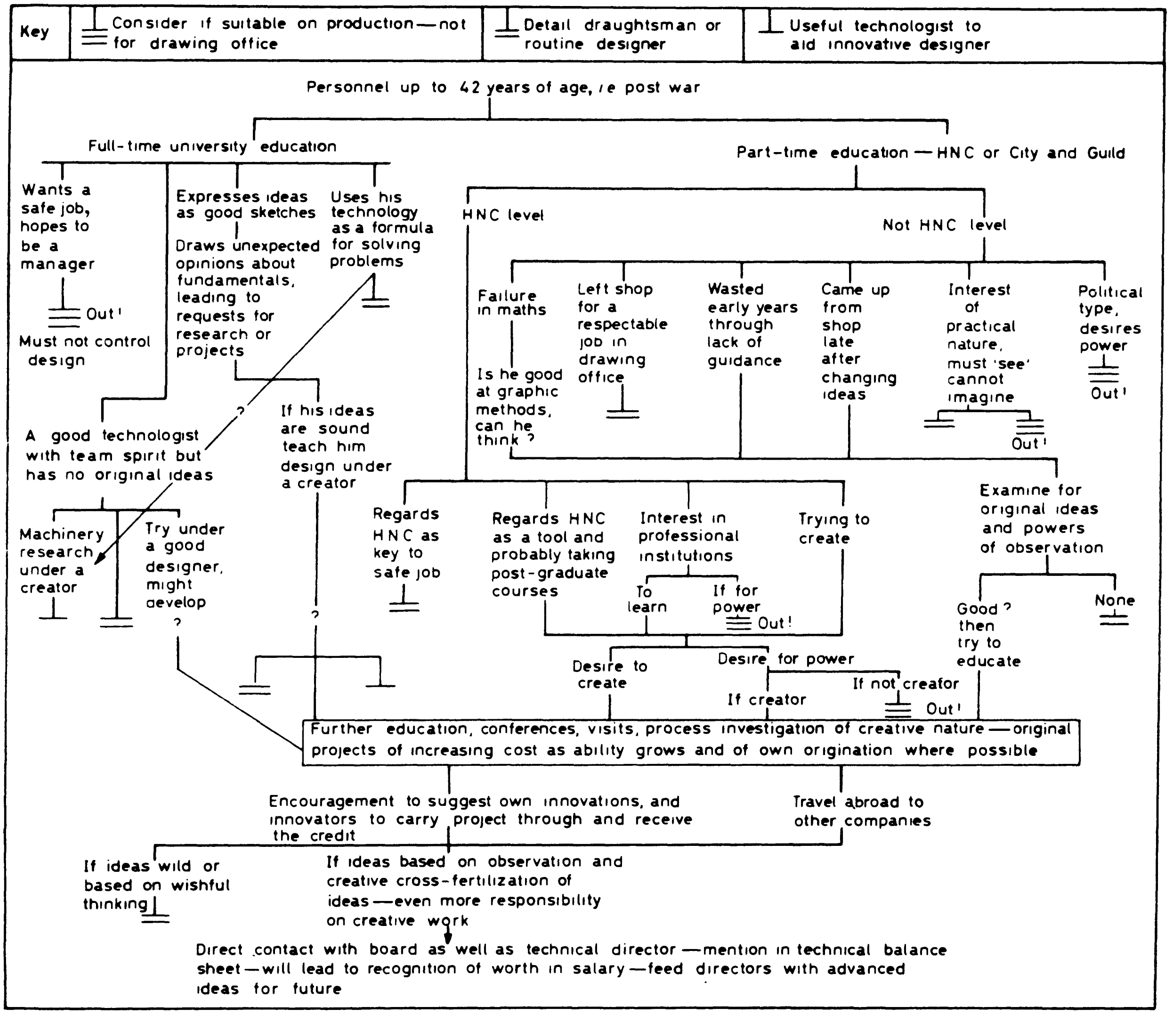


Figure 28.1. Suggested survey of drawing office staff by technical director

graduate and non-graduate technical personnel. These barriers spring from the fact that a graduate often has had a more expensive (university) education and expects, and often receives, a greater reward regardless of his effective use. The non-graduate resents this, having probably been promoted to a creative post by dedication and successes in this field rather than on qualification. The importance of the powers of observation and imagination developed during extensive practical experience and the value of these qualities to design teams is not always adequately recognized, possibly less now than formerly owing to the change in the nature of management, and optimism about current and pending changes in technical education. *Table 28.2* shows how incentives differ between creators, craftsmen, and labourers.

The behaviour of creative people and the methods of management necessary for getting the best results from them and for developing potential creators have recently been discussed in practical detail by McPherson (1965). A good creator questions existing practices, looks for weaknesses and alternatives, and has a pugnacious and self-assured temperament.

These qualities are the opposite of those of the organization man so readily accepted by day-to-day management. A firm which wishes to be progressive must have at least one member on the board able to over-ride conventional management attitudes to the creative mind and who understands creativity and continually searches for it.

The Management of Design

Table 28.2 also shows how the various levels of design activity fit into the pattern of management. In considering this it is worthwhile to remember the structure of the average company. The chairman of the board is the principal representative of the shareholders and is concerned with the financial well-being of the company and with the choice of the managing director who is to carry out the board's policy. The directors of a board are concerned with fixing the company's policy and may include specialists in various fields. As they are concerned with policy, and innovation and innovative design may have a profound effect on the company's future, these should be the concern of a specialist director. It is probable that the full effects of the director's activities on policy will not be realized until up to seven years after many decisions have been taken. Innovative design trends often have this delay before their effects can be measured. The managing director delegates much of his work to a team of managers, advisers and experts, such as accountants, work-study men, technologists, and sales managers. The effect of their activities may frequently be measured in up to two successive balance sheets. JAQUES (1956) considers methods of gauging the time for corrective action by immediate authority.

The work of such experts is largely concerned with the organization of facilities, labour and methods, to effect the making of immediate profit; to do this various inducements are used. These include fears of losing the job, of proving inadequate, of losing prestige and security and fear of criticism; there are incentives of promotion, increased earnings through bonuses, and personal credit with increased security. Finally, the experts can apply the technique of involvement, which used to be known as leadership. Companies which succeed without the apparent application of any of these techniques will probably be found to operate with a considerable hidden involvement.

The word involvement rather than leadership is used, as the latter implies that labour follows a leader, whereas in fact management involves the labour in the objective to such an extent that it drives itself to get on with the job and largely do its own thinking. It is an application of the fundamental desire of mankind to be creative (FRIEDMANN, 1961; DAVIS, 1964). A use of this desire was reported recently by a French company which reversed the trend of breaking down assembly of computers and instead permitted a single man to complete an entire unit and attach his name to it. Not only did quality improve, but a remarkable interest in advanced technical education was induced in the people so employed.

In another case, the managing director of a large company which used much machinery, exploited his skill as an engineer to set up his own engineering development unit. He rejected suggestions that a bonus system be introduced, on the grounds that the pay was reasonable and that the work was of such great interest that good leadership should provide all the incentive necessary. The unit expanded to forty-five craftsmen and twelve draughtsmen or designers. On the managing director's death his successor, who was an accountant and new to the company, continued with the projects already in hand and, on completion of the main one, referred to the unit as the place where miracles were achieved. Then, in an attempt to improve the unit, he started an incentive scheme accompanied by modern organizational methods under the control of an outside industrial consultant. The consultant installed an organizing expert in place of the existing manager, who was a creative engineer. The unit soon looked smarter, and issued well-produced folders on suggested projects showing incentives, completion dates and budgets (which were usually subsequently over-run). However, after four years it was decided to

Table 28.2. *The Management of Design*

Levels of management – innovation and some production only

Type of labour	Character of work	Example	Applicable incentive	Supervision	Supervision other than men	Current weaknesses	Management bias required
General labour	Job is codified	Line production	Pressure of oncoming work; fear of loss of job and security; piece money and wage rate; personality of supervisor	Line foreman to production manager	Report slackness of discipline; stop for faults; foresee stoppages	Lack of planning, of best equipment, and of technical and practical know-how	Accountancy; production engineering; experience
Skilled labour, routine work	All methods known and in regular use	Machine-tool fitting; detail drafting	Interest, promotion prospects, security, piece money and wage rate; a small backlog of work; personality of supervisor; co-operation with fellows	Foreman to manager	Choice of right man for job; work method, tools, supplies, quality and discipline	Technical education and tool facilities	Practical experience; simple direct control organizer; human attitude; accountancy
Skilled labour on novel work with random problems	Unexpected problems using known skills	Complicated repair work; pilot or prototype work; simple design; manufacturing dependent on poorly understood principles with poor instruments and variable material	Interest, involvement, bonuses, security, prestige, promotion, communication of objective; team spirit; desire to improve ability; personality of supervisor; wage rate	Foreman to manager, or development engineer to director	Observation and assessment of faults; devising work programme; discipline and quality; creative approach; drive; communication upwards	More technical knowledge, needing continual reassessment of progress to prevent drifting with not much paperwork; jobs often drift and progress data either meaningless or ignored; vested interests	Practical experience coupled with enough technical knowledge; awareness of passing of time and growing costs; flexible and observant organization; choice and training of men
Skilled labour with technical education	Routine work with problems demanding initiative or training	Design; experimental machine developments; technological investigation	Involvement, prestige, salary level, security, increased experience, credit; courses of education and visits; contact with top executives; team spirit	By-passes general management; engineer to technical director or managing director	Development; assessment of successor failure; observation of technical methods; personal interest in achievements of staff; communications up and down	Big parasitic overheads; directors hesitate to invest in progess; poor communication; misuse of labour	Creativity, technical insight, crystal ball gazing, practical experience, cost consciousness, courage and dedication
Innovative creators	Observing, thinking and creating; feeding directors with possibilities; solving problems	New techniques, new machines, new products; tracing cause of failures	Prestige, credit, flattery of ego; enough money to be free of family worry, security; freedom to choose own approach and some selection of work contacts; direct contact with authorizing authority; travel of business; facilities to learn; possible promotion to director level	Direct to director for authorization, knowledge of problems and display of ideas; general management to have nagging powers on discipline and to get work done but not to hinder or criticize projects in hand or proposed	Set company policy; search for creators and innovations; estimate feasibility; finance development; to sell successes	Too many non-creators getting control of facilities by virtue of qualifications or political activity; growth of non-creative technology; poor communications; big overheads of non-technical services; failure to invest in progress	Creative of products and policy; experience of customer's work; open-mindedness; courage and insight into the future

Execution – under general management

Policy – under director, free of general manager

Immediate profit – calculable

Service

Investment for future – incalculable

close the unit down and expand another small engineering unit to do some of the work. Three years later still, a new development unit was started with some of the original labour, but the old spirit of involvement was not recovered. Today, the projects started by the old engineering unit are amongst the most profitable carried out by the company.

It is interesting to note that the engineer who started the original development unit did not bother with any great degree of accounting, but he fixed his targets, the size of his unit and the rates of pay; he kept down the overheads and drove the unit hard. He never had to drop a project because expenditure was getting out of hand. At the end of the year he could easily see what had been spent and what he had earned for the expenditure.

The director in charge of innovative design must remember that the vital objective is good design, and that systems of organization and management are only there to assist this and reduce costs. He should himself have reliable opinions on feasibility. He must be aware of the fact that if management procedures become the most important objective of the development unit, they will carry the most prestige and distract good designers from their vital business. The greatest prestige must go to the designer who does the most difficult and important job. Morale will be good if the auxiliary organization is arranged to help the designer rather than hinder him.

The technique of involvement depends on fostering the feeling that initiative is expected from everyone; that credit without any distinction regarding background will be granted in full to those showing initiative; and that the initiator will be involved all the way in carrying his ideas to fruition. In applying this technique, it is necessary to know the people involved well, to look for creativity and to develop it, and to have everyone really believe that the unit does operate in this way.

The successful innovator is the man who has made a habit of trying to solve problems other than those thrust upon him: he finds problems to solve if none appear to be available. Experience develops in him a peculiarly direct approach to the vital factors at the problem's root. This approach is independent of technical knowledge, but technical knowledge in addition to clear and direct thinking will be required to interpret what has been seen or postulated.

A simple example of this directness occurred recently when a member of a workshop group overfilled his lighter and discussion arose on why it would then not work. A graduate who had joined the group at tea-break didactically announced that failure was due to an over-rich mixture refusing to fire in the same way that an over-choked car will not start. A fitter, after some thought, tentatively commented that you could ignite the lighter with a match. Could it be that with so much wet petrol the spark was quenched before any region reached a temperature high enough to ignite? Here the fitter had collected some relevant information and used his imagination on it.

Graduates who lack early practical experience quite often fail to examine the practical details of a present situation. This may be due to the use of a syllabus-based examination for the choice of people to be trained to graduate level. There is a lot to be said for a double filter in the choice of graduates: one part being based on class work and the other upon examination in which the questions are both hypothetical and highly improbable.

A similar weakness is that of failing to examine all factors and then to apply well-known techniques in a novel manner before turning to some modern miracle method which is not yet fully understood. It is true that many modern developments are not used readily enough; but people have, for example suggested the use of infra-red, dielectric or microwave heating as answers to a drying problem, without knowledge of the absorption characteristics concerned, and without having studied the possibility of overcoming the difficulties by using cheap steam available as a by-product of power generation. This resort to the use of incompletely digested technology as a formula for solving problems, instead of applying a creative approach coupled with a systematic examination of alternatives, is much too common; graduates are possibly more prone to it than HNC engineers.

Directors often do not know the extent of the weaknesses in the machinery they employ, nor how much could be gained by redesigning such machines. This is usually only possible to people with the requisite technical knowledge, and with the opportunity to take part in the running of such machines. The easier a project is to understand the more likely it is to gain acceptance. Thus, non-technical managers find it is easier to organize a small store containing a static stock of no great value, than to deal with the improvements which might be effected at similar cost to a process plant, although with much greater potential return. This tendency to deal with the understandable and petty rather than the difficult and important has been alluded to by PARKINSON (1958).

The task is to perceive possibilities, both in situations and in men. It is usually better to rely on a proven creator to perceive situations than to depend upon a committee. Such proven creators will surface if they are at first encouraged by a congenial atmosphere, the assurance of credit, and facilities to carry through their early ideas under their own control. They can be given increased responsibility as their score of successes rises. Creators, too, have a facility for recognizing other creators. If such men with the requisite experience and character are raised to director level, they will recognize and develop other creators. Such a build-up will also require a tradition of continuity of service with a company, and will need non-creators to be fitted into service teams while creators are given freedom to follow their particular bent as far as possible.

Directors in charge of a company's technical policy must have qualities other than pure creativity. They must be open-minded and interested in people; they must have a direct approach to the root of problems, a great breadth of knowledge, and a clear understanding of the fundamentals of techniques and principles rather than a specialized knowledge of application. They must be quick to observe and build upon all the implications of a proposal, and should have a wide experience of the background, current and past practices, and materials, of the processes concerned, in addition to the necessary pure engineering techniques. In many cases this demands a long association with the process, best obtained by non-productive service as part of an operating team under the eye of a creator who is looking to his company's future.

Such directors also need clearly defined resources to support work they think important. There should be money, staff paid from an overhead fund, and other facilities, sufficient to enable the director to follow up any idea thought likely to lead somewhere without having to make a detailed case of where he is going with estimates of costs and incentives. Day-to-day management should not be able to hinder him or stop him when he thinks he has found a trend which will lead to progress, or when he is investigating what is actually going on in a process. This is a situation which may be pregnant with difficulty. He should be answerable to the chairman of the board whose concern should be how much the company can afford to spend to ensure its technical future. Enlightened production managements are entitled to press for development to be done in the light of their own experience, but not to hinder the development department from following its own ideas.

Possible Future Aids to Design

More than propaganda will be needed to convince many boards of directors that they should make the best use of design in their organizations. Even legislation might be required to help, and there are indications that the government might support this if forward-thinking directors would formulate an appropriate scheme.

My own approach as an engineer would be to examine the entire system to find out if there are any factors which could be introduced or used in a different way to change the operation of the system in the direction required. I offer this opinion with as much trepidation as a production engineer should have in suggesting a major machine change to a designer. One such factor which does not seem to be used to the full to forward the cause of design is the shareholder. The shareholder is interested in profit and a successful innovation can give high profit margins for a period. It costs money in the early stages to forward an innovation, and profit may not materialize for up to seven years after investment in an innovation has started. This money must come from current profit, tending to reduce the price of shares in the company concerned if the shareholder decides to sell his holding. This loss in share price leaves the company exposed to takeover bids from people who know the financial position of the company and who know that by dropping the investment in innovation they can raise the dividend and gain an *immediate* profit. If immediate profit is their objective they are not interested in the future of the company over a long term. A change in the structure of the new capital gains tax might improve this aspect of the working of the system.

If each individual field of industry had the annual capital gains of the companies working in this field averaged to provide a capital gains index, and if shareholders who had held a share for five years were entitled to reduce the tax payable by the *sum of gains made annually above the capital gains index*, they would have a real interest in holding on to the shares of companies investing in the not-too-distant future. This would help to stabilize share prices. Shares would not have to be sold to realize the gains, the bonus for holding accumulating each year the company made a gain in excess of the index.

Interested companies might publish a technical balance sheet dealing with successful achievement and current spending, perhaps mentioning successful innovators by name if they were pursuing new projects for the company.

Another possible way of encouraging creators is by way of life-long education. Contrary to some professional opinion that the mind loses its receptive ability with age, creative minds seem to retain this ability, at least in their creative field. An interesting example of this was given by Dr. Barnes Wallis at a recent conference. He described how he had to learn the successive theories of flight as the areas of interest changed: thus he passed from the lighter-than-air field to the heavier-than-air field, from subsonic, through supersonic to hypersonic.

This receptive ability should be considered in forming postgraduate courses. These courses should encourage the cross-fertilization of ideas between designers, users of machinery, and purchasers of machinery. The first move would be to encourage users to employ more qualified and suitably trained engineers. These men would feed back criticism of designs to manufacturers, a service that is needed in Britain; at the same time they would suggest new ideas. This recognition of the importance of engineers in industry is more common abroad, and could be copied here with advantage. I have worked as chief engineer to a group of small companies under continental employers in this country, and was surprised at the high status of the post, the importance attached to my opinions, and the weakness of an HNC alone as aid.

Comprehensive post-HNC or equivalent part-time courses should be available to train men for the specialized posts of chief engineer, designer, machinery research and investigation engineer, production engineer, and sales engineer. Creative minds would grasp the importance of the mastery of several of these courses, the importance of combining practical experience with design ability, and the importance and sheer interest of continually increasing one's span of knowledge.

Conclusion

Engineering innovation and design is not a matter for day-to-day management but is a matter of company policy and long-term survival, and should therefore be very strongly represented on the board of directors. The achievement of innovation successes is a long-term business and ranks in importance with growth policy, finance policy, and company image. Its problems are so different from those of day-to-day management that it must be independent of this function. Too many companies regard innovation as a short-term activity, capable of having its return predicted accurately, whereas much of it is a trend activity with a new feasibility materializing out of the successful realization of the previous innovation. Such progress comes from the visualization which joins functions and makes balanced compromises in a single dedicated mind: teamwork is needed once the innovation is visualized. A committee might control the teamwork needed for the execution, but the creators should be answerable to a single man responsible for the specific policy.

This man should be a genuine creator of high calibre, not a good organizer or a salesman of ideas; he should be answerable to the chairman of the board and be in very close contact with his creative staff. This close contact will do much to implement the frequent suggestion that the designer's status should be raised.

Through his knowledge of the ways of the creator, he will appreciate and assist the work of his team. This will need the adequate supply of information, facilities for visiting customers and places where work of interest is carried out, the provision of specialist courses, the encouragment of diverse experience, and a rational approach to examinations. He will encourage independence and openness, and prepare for the arrival of those ideas which have yet to be formulated (DAVIS, 1963).

The importance of design in a company's future cannot be too highly stressed. The shareholder is the final arbiter on many of the matters concerning the future of a company, and it is important that he should know of this importance of design and should demand some means of measuring how the board of directors which he supports is handling this factor. The quality of engineers will improve under a leadership which produces involvement in a company's business. Since so many criticisms have been made of our engineers by directors, it is surprising that more thought has not been given to the part that directors may play.

This chapter is based, like most engineering design, on the facts of experience and personal interpretation of these facts. There seems to be little of an objective character so far published on the subject and a case can be made for research studies on the proposals given, in so far as this may be possible.

Chapter 29

EFFECT OF ORGANIZATIONAL PROCEDURES ON DESIGN – AN OUTLINE OF THE PROBLEMS

I.M. Ross

Introduction

The last few years have seen the beginning of a shift in emphasis in the study of design – from the end product as such and the components, materials and knowledge which come together in the evolution of its form, to the process itself and the methods of reasoning and imagination by which the form is conceived and refined. Many factors may have contributed to this change: the increasing complexity of techniques and function and the widening and sophistication of user requirements are forcing the use of a more systematic approach; the low standard of much recent design is focusing attention on the decision processes which may have led to this outcome; the entry of the computer offers the possibility of automatic design in suitable cases, but to do this the process has to be broken down into its bare essentials. There has also arisen a feeling that the technological tower of Babel created by over-specialization in the pursuit of facts is probably inimical to good design, and this is leading to a search for generalized methods of training which will emphasize and develop the common features of the design process, even if it means relying more on machine methods of information storage and retrieval to provide the detailed knowledge, experience and philosophy required.

Thus a phase has been entered in which design, as design, is a subject for study. The goals of such a study must be to understand the nature of the design process and how its various elements can be developed and assembled, motivated and controlled to give the greatest overall benefit. The role that the human designer must play and how his skills are best acquired, developed and exercised must also be known. As part of this, the extent to which he is influenced in his work by the organization and environment in which it takes place must be known, and it is this aspect which is the subject of this chapter.

In looking at aspects of design which have tended to be taken for granted in the past, it will be desirable to adopt an attitude of doubt and suspicion: to refuse to accept any notion, other than very tentatively, until it has been shown to be not only internally self consistent, but to key into the evolving pattern of knowledge as a whole. A final understanding is going to require the contribution of many disciplines, particularly from the social sciences, and is not something I could hope to attempt. Rather, this chapter is written from the point of view of one with a fair amount of practical experience in the conduct of design, a consciousness of some of the problems and an instinct to question; but without the detailed and documented knowledge required to provide a firm framework of understanding. Where I do suggest answers, it is more with the intention of illustrating the form these may take and in the hope of stimulating others, better equipped, to rectify and complete the picture.

The Nature of Procedures

Procedures are the rules by which the various processes in an organization are sequenced and interlinked, and which promote and regulate the flow of activity and determine under what conditions and in what form it takes place. The rules are based on some preconception of what is best, modified similarly from time to time in the light of experience. They may be explicit, or merely implied by the existence of other rules, or they may take the form of convention, tradition, or be purely psychological. It is desirable to know what procedures are in use for the processes involved in design, what effect these may have on the output, and whether (and if so, how) some degree of optimization may be obtained.

Particular processes may show peculiar sensitivity to procedures and it may well be that design is of this nature, but first it is advisable to look at the problem in a more general way, narrowing it down later when there is a clearer idea of what to look for. It is also best at first not to be too pedantic as to which influences should be called 'procedure' and which by some other name (but distinguishing where necessary between influences and the processes as such). It will be sufficient to distinguish different classes at a later stage when it is clearer what type of classification best suits the problem.

Consistent with this general approach, environmental influences can, for the present purpose, be regarded as forming a sub-class of procedures. This is probably reasonable, since they certainly represent the outcome, extension, or manifestation of procedures 'written' in the form of bricks, steel and glass, patterns of light and shade, intellectual, social and psychological background, and the like. They are certainly not processes as such, but may have a profound effect on them.

At a later stage of study, it will be desirable to know what processes specifically characterize design. For the present, one can think in terms of a network of elementary processes of the form symbolized in *Figure 29.1*; there is a basic process (complete with storage capability), two inlets to allow blending, two outlets to allow switching, and a pair each of supply and signal links. The latter provide monitor signals *M* outwards, by which the state of the process (and in total the network of processes) is determined. Knowledge of the state is conveyed to a procedural box (not shown) and this issues signals *I* which influence the process in the manner laid down.

The influence signals may be of different patterns. They may depend only on *M*, with dependence changing infrequently in discrete steps as procedures are reviewed; they may have a fluctuating component superimposed, for example as the environment changes; or they may be experimental or adaptive following some procedure laid down at a higher strategic level.

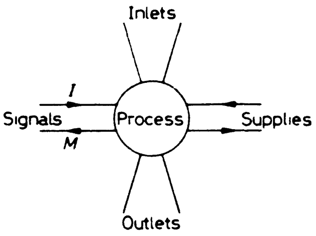


Figure 29.1. Network of elementary processes characterizing design

If the process were purely mechanistic, the network problem would be that of process control and hardly relevant to the present consideration. However, since people are involved in the process, there is both a work-study or ergonomic problem of treating people as machines, and a motivational one concerned with the psychological aspects. It is the latter which may be the more important, since it is well-accepted from general experience that enthusiasm can make tolerable a considerable degree of apparent inefficiency or confusion, whereas the most perfect system, on paper, may easily be wrecked if it achieves only perfunctory, or even hostile, compliance.

In essence these effects arise because the operation of a machine is an end in itself, whereas to a man work is merely a means to some entirely different end. Any procedural control which thinks only in terms of adjusting the means, forgetful of the effect on the man's aspirations, is not likely to be very successful*.

*** The nearest simple mechanical analogue of man in this respect is probably the gyroscope, which also has its own external 'aspirations'. Notice the curious, resistant, oblique behaviour under direct applied constraint.**

This is probably particularly true in the design field because of the high aspiration level of designers as a class and their vocational ability to sense the presence, and foresee the implications, of constraints.

Thus, in looking at procedures and their effectiveness, particularly those concerned with design processes, it seems especially important to look out for psychological difficulties such as may reveal themselves by low morale, lack of enthusiasm, care or originality, or in difficulty in holding or recruiting staff. To this list other diagnostic factors may be added when the problem has been more carefully considered. Important to this approach also, will be a knowledge of the aspirations or motivating forces of the typical designer. This is a problem for the social scientist, but for the present purpose and to show in more detail the implications of such aspects, some observations from general experience may be useful.

Man's Motivations and Moods

It is suggested very tentatively, that the significant forces which on the surface motivate a man are directed to the pursuit of esteem, security, knowledge and happiness. Possibly these could be traced back to deeper forces and perhaps to a single force – the wish to survive and the pleasure associated with incremental achievement of this. For example, esteem, which is the degree of respect in which he is held by his fellow men (and self-esteem, by himself on their behalf), may well be related to the primitive need to keep in with the herd if he was to survive: to show qualities entitling him to membership, in particular willingness and ability to help, ability to lead in a direction thought to be safe, no unstable tendencies such as might endanger the group safety, but always allowing the possibility of his being able to convince the group about some other course of action. Similarly, the desire for knowledge is doubtless connected with its importance for survival – a curious object may contain danger and need investigation – and more generally, knowledge is the counter intelligence against nature on which man bases his strategy of life. The desire for security is, of course, a direct surface manifestation of the survival instinct; happiness is connected with the temporary achievement of security, or rather with the temporary avoidance of danger and particularly with the accomplishment of something which may have this effect.

In addition to these four goals, the problem-solving nature of man's existence should be noted. He is like a computer which is forever seeking the best solution, up-dating the answer continuously as his experience evolves and his environment changes. Because of the importance of this process, he likes to use every opportunity to practise – hence, perhaps, his interest in games of skill, his attraction to puzzles, his acceptance of challenge. Linked with this is the competitive instinct, which has also a fairly obvious direct connection with survival under conditions of limited resources.

Of these forces and instincts, the desire for security would be the most powerful were it seen to be really imperilled in the near future, but under modern conditions and in the present context it is probably a lot less powerful than the desire for respect, including self-respect. The other two forces are probably still less powerful and may need a rather sophisticated appreciation to have an important effect, though they should not be neglected in dealing with the higher levels of intelligence. The competitive instinct remains a powerful factor.

Before discussing the importance of such points in consideration of procedures, it should be noted that man has usually had a choice of the groups he might aspire to join, and that in its modern form he can even be simultaneously a member of a number, for instance his family, his friends, his neighbourhood, club, union (or institute), firm, creed, culture, country, *etc.* His attachment or alignment to any particular one will be related to the benefits he visualizes, which will depend on view-span, and to also the extent to which it may imperil his membership of another to which he attaches importance. To illustrate the significance of this, a procedure which effectively prohibits publication of his work to a man who attaches importance to his cultural group, is likely to weaken his alignment with the organizational goals or, put another way, his 'specific coherent activity' for the organization falls. Fear of security may maintain a minimum alignment, or where this is not effective – or is only negatively effective – he may be powerfully influenced to leave.

In this example the motivational aspect is fairly obvious, but frequently the effect of procedures seems to be less directly connected with an end result. Instead, they set up a mood, spirit, or state, a kind of mode of operation of the mind, which colours or influences the approach to problems whilst it lasts. The mode may be either harmful or beneficial to the organization. For instance, a procedure may create a resentful mood, likely to be harmful; equally another may create a competitive spirit, possibly with good results. Still more generally, a procedure may create a state of tension in the mind, a focusing of attention on to a specific end point, which may either be beneficial or harmful, and contrariwise another may confuse, or bewilder, or possibly soothe.

It would be presumptuous for me to attempt to disentangle such considerations and set them out in a coherent way: this is something which is going to require professional attention. But it may be useful, as a temporary bridging operation between the realm of the mind and the practical world of design, to discuss the interaction briefly through a set of terms such as those now introduced. This set makes no pretence to provide a logical framework, although this is something that must be hoped for in due course.

Factors having a Psychological Content Involved in or Conditioned by Procedures

With the reservations of the preceding paragraph, the following factors are suggested. In order to give some semblance of order, these are broadly grouped into three classes:

(1) Personal factors – freedom, self-respect, progress, creativity.

(2) Task factors – worthwhileness, difficulty, methods of driving.

(3) Organizational factors – confusion, politics, frustration, morale.

The sub-headings chosen are more for convenience of paragraphing, that with the intention of systematic mapping.

Personal Factors

Freedom – Man has an instinct for anything that might limit his freedom of action or trap him in any way, and since procedures are almost by definition of a restrictive nature, his first reaction is one of suspicion and antipathy. He will comply if he has to, but it will be with bad grace and he will be alert for the deficiencies, will be readily confused by the obscurities, and quick to notice and experience the absurdities. The drafting and introduction therefore require care: the importance should be clear; the restrictive element should be confined to what is essential; there should be user participation in the final drafting, particularly on 'sensitive' detail; a controlled 'leak' should be incorporated to cover the absurd case and so on.

Self-respect – This powerful factor is invoked to some extent by all procedures, and strongly by those relating to status, status symbols, salary and salary scales, promotion, side benefits, trust and responsibility, and in particular decision-making. It is also involved in questions of publishing and exhibiting his work, when it can easily over-ride the importance of commercial secrecy. It is usefully increased by procedures which ensure that good work is noticed and credit given when deserved.

The fear of loss of respect is an important negative factor if the work is very challenging or difficult. It is allayed by good facilities, wide experience, support, co-operation, friendship, understanding and the sharing of risks.

Progress – A man likes to feel that he is making some progress, that his work is being used and appreciated, and that he is increasing his potential for the future. He will therefore be interested in the width and variety of experience he is gaining, as well as in the depth or special knowledge involved. He will want to see also that the possibility of advance exists, and that he is being given the opportunity to acquire the background necessary to take advantage of this. Such points will be involved in procedures relating to training, further education, transfer within the organization, staff grading, recruiting policy, and so on. If the prospects look too stagnant he may leave rather than complain, so it is important to see things through his eyes and sense the danger in advance.

Creativity – This is a very important factor in design and needs special discussion, particularly since it is likely that many current procedures tend to inhibit rather than promote this faculty. There is a widely held view that this is a gift given only to a few at birth, and that the best one can do is to find such people and then pander to them. In fact, there is plenty of evidence that this is far from true, that originality is at its best under dire necessity (the 'mother of invention'), that it is quite amenable to training and experience, and that the initial difference between one person and another is much less than might appear.

A man joining a group is motivated to justify his membership and to show his worth. With his fresh point of view there will be a tendency to innovate. On the other hand, the group will tend to regard innovation with suspicion – will it usurp or destroy? If he comes in with special knowledge not available to the group it will be easier for him – he can use this as the core of his innovation. It will be especially easy if his confidence has been built up by the excellence or aura of his training, and particularly by having worked for a time with a great innovator, watched his methods, seen his human side and his failings, and lost the awe and feeling of inferiority which he might otherwise have had.

Later when he becomes established in the group the need to innovate becomes less, and he may in fact find it psychologically difficult to do so, unless he has meanwhile become accepted as a leader or perhaps as a harmless rebel. It will then be better for him to move if he wishes to retain his creativity. This will create fresh challenge and a further need to learn.

The lessons for procedure would seem to be the need to move people around in such a way that they work closely for a time with the best designers; the need to avoid narrow specifications in recruiting; the need for staff to change their field periodically (after three or four years, say). Some of this change can be hierarchal, for example component—equipment system or *vice-versa*, some 'product' class and some a gradual change in specialization. There are reasons to believe also that a cycling between research and application is desirable, in giving full exercise to the natural capabilities of the human mind. Such a change in method may also have other advantages: it allows better assessment of ability; it provides practice in the approach to new problems, forcing a more systematic approach; it provides width of knowledge and experience which is very desirable for rapid insight; it helps to break down petty fashions and snobberies between jobs.

It is probably easier for a team than for an individual to innovate, because of its greater width of knowledge, its greater confidence and its relative resistance to psychological pressure. To be effective, however, it must be carefully composed to embrace the experience and skill required, and must be trained *as a team*. To maintain its creativity there should probably also be a slow drift in field, and a slow replacement of individual members. These problems will require study, particularly with the importance of the team method in the design for automation, a characteristic of which is likely to be short periods of intensive and highly specialized development, followed by long runs in production.

A major deterrent to creativity is probably the type of procedure which requires a strong case to be made before any work can be started on a project. A new idea often contains an unknown element and even a trace of the ridiculous, points which will only be resolved later under the intense challenge of the job. Equally discouraging is the knowledge that a new idea is going to be under close scrutiny before it has had a chance to develop, or, in the opposite extreme, that it is going to be given too much importance too soon. An atmosphere of faith, trust and understanding is required, with gentle pressure to innovate rather than not to do so.

Mention should be made also of the possibly inhibiting effect of 'checking the literature' before beginning to think creatively about a project. Although this may be good work-study practice there is the danger that it may channel the mind into a groove which then becomes difficult to leave. A fresh approach is probably preferable, leaving the study of what others have done until later, when ideas have had time to flow and take shape, although this may mean some back-tracking on occasions. By this method, the literature will also be found more meaningful.

Finally, it is probable that the bottling-up of ideas which occurs when commercial or national security procedures are applied, fails to make room for other fresh ideas. Publication, apart from being a powerful stimulus, both frees the mind and creates a vacuum to be filled by fresh thinking. There may be many other detailed environmental factors having an influence on creativity which will emerge on closer study.

Task Factors

The Worthwhileness of the Task – For a man to give his maximum effort to a job he must be able to appreciate its part in the scheme of things and understand how his own contribution is helping towards this. Procedurally, this means that he must not just be fed with information technically sufficient for the purpose; he must be given sufficient information on background, progress, costs, *etc.* for him to take a live interest in the project and in his own contribution towards it. Not every job can have the same excitement, of course, but the procedures should ensure as far as possible that each man gets his share of those which are. This will react on the methods of loading, of staff transfer and so on.

The Difficulty of the Task – Just as the job should be exciting there should also be a reasonable degree of difficulty attached. Not too much, or fear of failure will inhibit his whole approach, but sufficient to form a strong challenge, and yet be within his powers, with a little help at critical points. This will focus his interests and bring out his best. Again, this is something that must be taken into account in the movement of jobs and of people.

To make a job artifically difficult by lack of aids will not help: morale will only be high if it is known that all reasonable help has been provided.

Drive – One of the functions of procedure is to set the pace – to get the work flowing smoothly at the maximum practicable rate. However, man does not like being monitored and, still less, being pushed. He tends to react in such a way that the effect of such methods is self cancelling. But he can be inspired and drawn on by good leadership, the essence of which is a sense of purpose and direction, strength of character, good tactical judgment, an almost sacrificial sharing of risks and rewards, and an ability to let each man feel inwardly the importance of his own contribution. This has a remote, but none the less powerful, procedural aspect in so far as methods of staff selection, training and assessment determine in the long run the leadership structure.

On a different plane is the question of direct incentives – bonuses, profit-sharing and the like. These can be strong short-term stimulants (and sometimes sedatives), but they are difficult to apply fairly and in the long run may generate as much resentment as satisfaction: a carrot in front may be a good stimulus for a donkey, but how long is it going to be effective for a thinking man? If there is to be any feedback of extra benefits, it should probably err on the side of liberality, and uniformity, rather than consist of a few awards to selected people.

A man is at his best when he is driving himself – the volunteer, rather than the conscript. The aim of pacing procedures must be to create this condition, or rather allow the condition to occur spontaneously, since any artificial forcing or cunning will be self defeating in the long run. There must be the maximum giving of trust and responsibility and the encouraging of a man to commit himself, but not of course in any rash way, with full understanding of the need for unobtrusive help and encouragement and the sharing of risk and danger. It must also be appreciated that it may take time to convert from the driven to the self driving mode, and that there may thus be a dip before the rise.

Typical of the legitimate aids in this process, and the aim of procedures, should be the appeal to the problem-solving instinct, the game-winning instinct (*i.e.* the competitive spirit), the team spirit, the sense of occasion, the sense of personal accomplishment, and so on. For example, competition is a powerful stimulus, but has to be seen and felt by the competitor to be effective. It may be necessary to encourage some internal competition where it would not otherwise be available. The view that all overlap or competition is wasteful is a dangerously narrow one, but all too common. Similarly, the creation of teams, particularly where these compete in some obvious sense, provides the maximum self disciplinary force, by combining the desire to partake in victory with the desire not to lose respect by letting colleagues down.

The importance of the other two factors mentioned is seen from the extra effort which can be drawn out in preparation for exhibitions, conferences and similar immovable and prestige-involving external events. Not only can such stimuli and pace-setting means be encouraged (instead of being regarded as interruptions in the work), but the process can be extended within the organization and used as a principal energizing mechanism.

Organizational Factors

This term is used as a convenient title for some factors which characterize an organization as a whole, but undue significance should not be attached to the classification.

Confusion – An organization can be regarded as confused to the extent to which it lacks a complete, well-known and coherent set of procedures. Although a certain amount of confusion gives scope for personal initiative, it is much better that such scope be embodied in the procedures rather than occur for want of them. Scarcely any inhibition can be more powerful than not to know the limits of one's authority, the means of getting things done, who else is likely to be involved in decisions, and what factors may later upset the decisions. Unfortunately those most likely to be inhibited, discouraged and driven away are those who see furthest and most deeply, since they are least likely to be satisfied with temporary decisions, or superficial solutions. This can be of great importance in design, for which both width and insight are highly desirable qualities.

Confusion also creates alibis for failure, and in this way tends to undermine the sense of commitment which has been stressed as important. On the other hand, the organization must not be so 'tidy' that it becomes claustrophobic: each man needs his own little 'castle' in decision-space in which he is able to puzzle things out, free temporarily from the stares and lifted-eyebrows of his neighbours.

Politics – A concomitant of confusion is politics – the prevalence of unobjective, selfish thinking and behaviour. Sometimes this state can develop from a single infecting source, and it must be the aim of procedure to detect and eliminate it at an early stage. Frequently, however, it develops spontaneously from the misunderstanding and misinterpretation associated with confusion (particularly with the spread in view-span referred to above), and the feeling of insecurity thereby created.

Frustration – This can be regarded as a mood generated when work, or ability, is impeded or wasted through procedural defects. It leads to low alignment with the organizational goals, reduced enthusiasm, initiative and sense of responsibility.

It is important that procedures be screened beforehand for this possibility and also watched carefully in operation, looking for signs of frustration. A typical defect is the operation of a design approval procedure too late in the design network, or lack of care in the agreeing of the original target specification.

Morale – This is an index of the overall, deepseated, mood of a man. It is low if the work is unnecessarily difficult, unrewarding and prejudicial to his long-term prospects; if he is being asked to make unnecessary, or useless, sacrifices. One example would be a man kept at the same task indefinitely, for convenience, because of some special skill, when someone else could easily have been trained to take over. His standard will tend to fall and he will be strongly motivated to leave, often without complaint.

It is important that one of the personnel procedures should be to visualize continually a man's job as he is likely to see it, not just as it appears to the organization. There is a need to develop methods of measuring objectively aspects such as morale, not only for individuals but collectively for groups and for the organization as a whole.

Procedures in Design

The discussion so far has been concerned with procedures in general, but with emphasis where appropriate on design. In a full study of the problem there will be a need to look at the whole design process network in detail, examining the procedures likely to be involved and by applying principles such as those tentatively put forward here draw conclusions for future guidance. It would be premature to attempt this here, but it may be useful to take the discussion a little further, if only to bring out perhaps the nature and extent of the problem.

The Process Network

Any actual network will show considerable branching with spurs and loops at various points consistent with the inspirational and iterative nature of design. There will also be transverse supply and communication lines in accordance with *Figure 29.1.* The process may be represented in the main by a single unbranched flow line, as shown in *Figure 29.2.*

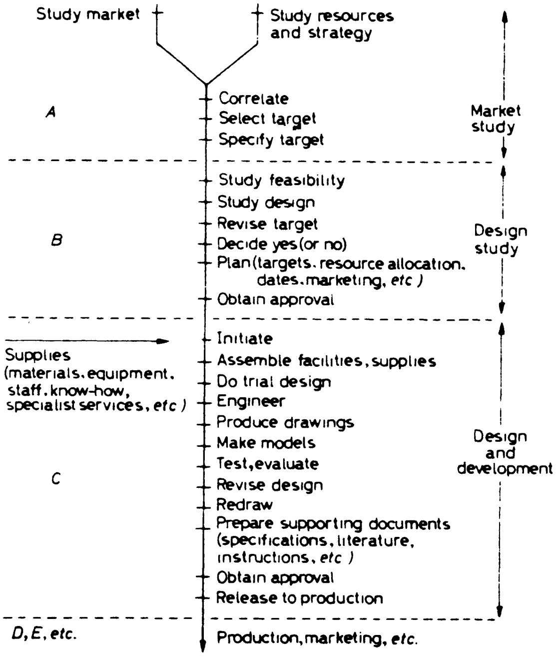


Figure 29.2. Symbolizing the design network (skeleton only)

In this diagram the process chain has been divided into a number of zones, marked *A*, *B*, *etc.* Of these *A* represents the market study stage, which may or may not be regarded as part of design. Zone *B* is the design study stage, about which there is little doubt. In zone *C* no attempt has been made to distinguish between design and development (which is regarded here as the experimental trying out and consequent refinement of plans prior to completion), since design cannot be regarded as complete until development, if any, has taken place.

The following problems on procedure are suggested by an examination of *Figure 29.2:*

(1) Should there be a formal network for the organization, or should design be informal, or *ad hoc?*

(2) If formal, should there be through-control, *e.g.* market-study to marketing, or should responsibility be zoned (departmentalization); and if the latter where should the frontiers lie?

(3) If through-control, should there be a single vertical network, or several in parallel (divisionalization)? If the latter how should it be defined – discipline, product, or field of application? Should there be overlap (technical competition) or purely profit (or performance) competition?

(4) What authorizations, check-points and general controls (financial, programme, technical) should exist and where should they be applied in the network? What should be the remaining decision structure, relative to the design network, *i.e.* who should decide what?

(5) Should the people be stationary with the work flowing past, or should they move down with the job: many functions, same job; or same function, many jobs?

(6) What degree of teaming should exist? What composition, training and life-cycle?

(7) How should specialist skills and services be fed in? Should people move in, or work move out? How should extra-mural work be placed? Who decides and pays?

(8) What aids should be provided: computation, data retrieval, special instrumentation, consultants, secretarial, *etc.*?

(9) What constraints are tolerable: secrecy, publications, exhibitions, discipline, budgets, *etc.*?

(10) What environments are desirable: buildings, localities; intellectual, discussion groups; psychological; social; housekeeping, *etc.*?

(11) What procurement procedures are desirable: consumables, capital goods; calibration, standardization, *etc.*?

(12) What staff procedures are desirable: recruitment, selection, grading, salary scales, assessment, promotion, pensions, side-benefits, status symbols, posting, training, further education, cultural activities, health (body and mind), and so on.

These are some of the many aspects which will have to be examined, and to which a number of others may be added on fuller consideration. In addition there are questions such as how procedures are best drafted, introduced and kept up-to-date. There will also be many points of a more detailed nature in connection with particular processes. Throughout the whole study, the psychological aspects discussed must be borne in mind, in addition to problems of work-study planning, which have been rather played down in this discussion, but will become of increasing importance in the later stages of optimization.

Finally, there will be a need for considerable field work, to find out what procedures are current in representative design laboratories and what trends are taking place. An attempt must be made to distinguish the good from the bad (on the basis of actual results) and to try to understand the reasons which lie behind the differences. The career histories of notably successful designers will also be of great importance, including a study of their environmental backgrounds. The discussion here will have been useful if it encourages a wide and deep approach, and warns of some of the things which may prove to be significant. Above all, however, is the need for careful unprejudiced research.

Chapter 30

COMMUNICATION

C. H. Buck

Introduction

Design without communication is impossible, and many modes of communication are discussed in this book. Frequently the designer does only the mental work, and the execution of the design is then done by others. It is necessary to communicate the details of the design to the craftsmen so that they will know what to make. This is commonly done by means of engineering drawings, and in Chapter 26 McMullen has discussed ways of improving the output of the drawing office in quantity and reliability.

But the designer first needs to communicate with himself. Rarely is a design conceived instantly and without flaw. Usually the ideas come in parts, and not all of the parts fit. Some means have to be found to fix the fleeting thoughts, so that the designer may evaluate them thoroughly by all the relevant criteria. The commonest medium is the sketch, which may be elaborated into a formal drawing. An example from fine art is the painting of *The Lion Hunt* by Rubens, which is in the collection of Dr. Count Antoine Seilern, together with the original drawings and the intermediate oil sketch.

The engineering designer may prepare a chart to record his mental processes, and to guide him in his decisions on the lines illustrated by Matchett and Briggs in Chapter 21. He may construct models, which are particularly useful when the appearance is an important consideration. Also, they are invaluable as a check on the solid geometry of the design, which may have been incorrectly envisaged at the sketch stage. The model in the form of a working prototype is indispensible when evaluating performance. Usually performance measurements are made by a development engineer, not by the designer, so at this stage the model becomes part of the communication between the designer and his immediate colleagues.

In a manufacturing organization there will be formal communications concerning design, instructions from and reports to management, and the passage of information between various functions and design, such as costs (Chapter 18) marketing (Chapter 6), production and service (Chapter 27). The designer also needs a great deal of technical information, and in Chapter 12 Farradane has suggested the possibility of using computers to provide more rapid access to more information. Peplow, in discussing design acceptance, is really discussing the communication that goes on between a designer and his customer, In many situations the customer will be represented by the designer's marketing colleague.

All these modes and uses of communication are important, but one problem that continually occurs is the failure of communication between individuals who are concerned in different ways with the same design. In this chapter, the nature of the problem is described, and a partial solution suggested.

Consider an organization manufacturing speculative products in quantity. This seems to be the most complex design situation within a single organization. Here there is no physical barrier to communication, since the entire organization (except for distribution detachments) may well be on one site, perhaps under one roof, but obstacles to communication do exist. Some of these are personal incompatibilities, some are the bottlenecks of a rigidly formal organization, and some are caused by the naive assumption that certain notions are so obvious as not to need stating. However, communication is essential, because so many factors are involved, even in the design of a simple consumer product, that no one man can possibly know enough to make the best design decisions.

It may be that in examining this limited problem, some clues will be found for dealing with the problems of communication in more difficult and complex designs.

Speculative Manufacture

A great many of the materials and appliances used by the private individual are produced speculatively. That is to say, the products are made and exposed for sale in the hope that enough people will buy them. Some of these products are quite simple, like packets of sugar, while others are quite complex. The domestic appliances of the western world (cookers, washers, television) and the ubiquitous motor car are all speculative products. Mostly they are made in large quantities and each manufacturer offers a limited range of models. A great deal of expense is involved in preparing to manufacture, and much of this expense is directly related to the detailed design of the product. Once the tools have been made it is very costly to change the design except in minor details. But the market, that is the public, cannot have the opportunity of judging the product until all this preliminary work of tooling has been done. Therefore the manufacturer must incur all the expense of design and tooling before there is any opportunity of recovering this investment by selling the product. Frequently several years of manufacture and sales are necessary to recover the total initial investment. If this kind of enterprise is to succeed, good design decisions are essential. Everyone knows of the bad design decision made by Ford of Detroit. This mistake, the Edsel, is said to have cost £120 million. Few companies could survive such a disaster.

Factors Involved in the Choice of a New Product

The fundamental necessity for a commercial product is that it should sell in sufficient quantity. In some kinds of business much information can be gained from market research, but often the information is very limited, and when great novelty is involved the information is unreliable. For example, ICI invested several millions in a plant for manufacturing beryllium, but after a short period of operation the plant was shut down, because the expected sales were not maintained.

It is desirable to know what sort of product will sell, in what quantities, and at what price. Some allowance must be made for the time needed to design and to prepare for production, so that these forecasts must usually be made several years in advance. This long range does not add to the precision.

Even more questions must be asked. Is the proposed product technically feasible? Is money available to finance the design and development? Can staff and facilities be released or found? Can the product be produced in the quantities expected with the available equipment? Can the new product be handled by the existing sales and distribution organization, or must a new organization be created? What sums must be invested in advertising to stimulate and maintain the desired rate of sale? Will the new product require maintenance? If so, what facilities must be provided by way of information, supply of spare parts and trained engineers and mechanics?

Until satisfactory answers to all these questions are forthcoming, there is no point in authorizing any major design activity. These are questions for management.

Factors Involved in Design

The questions to be considered by the members of the design function will depend in detail upon the nature of the product. Fundamentally the questions are: what is the product expected to do; in what circumstances will it be used; what sort of people will use it; how will it be made and how much may it cost to produce; what conventional constraints will be laid upon the designer by law, by custom and tradition, and by company policy? Several different sorts of skill and experience may be needed to deal with all these questions. Typically these skills are likely to be those of the engineering designer, the industrial artist, the development engineer and the maintenance engineer.

For both the very diverse range of considerations that exist at management level, and the somewhat lesser range at the design function level, all the right answers have to be found in a single design. At the lowest acceptable level this will be achieved by compromise; at the highest possible level it will be reached by integration. Therefore at management level there must be communication between the representatives of the various interests, and at design level between the practitioners of the various skills. Because these people have different interests, different backgrounds and different skills, communication is inefficient.

The Management Team

In an organization making a small number of different products, each produced in quantity, the decision to initiate a new product is of major importance, not only because of the cost of design, development and tooling, but largely because the new product will be expected to contribute a substantial part of the company's income when it comes on the market. Therefore such decisions are frequently taken at the highest possible level, that is to say, the board of directors decides. In other companies, the decision will be taken by the chief executive who may be styled 'general manager' or 'managing director'. In the former case, the chief executive is likely to be responsible for putting the case for the proposed new product to the board. If a proper decision is to be made, the case presented to the board must be complete. The chief executive must state what sort of new product is envisaged; the expected selling price and the rate of sale; the estimated works cost; the launching date; the estimated costs for design and development, tooling and other preparations for production, and launching promotions; the nature of the competition to be faced; the sales organization needed; the distribution channels and the physical means of distribution; whether servicing facilities will be needed and of what sort; the effort needed to recruit and train labour; for some products, other considerations are also needed. If the chief executive has to make the decision himself, he must still collect all this information, and he may devise some way of presenting the salient points conveniently and compactly, perhaps on one side of a sheet of paper.

He will not write the story himself. His function will be more of an editorial nature, for the component parts of the story must be prepared by experts in the various fields, *i.e.* market research, economic forecasting, advertising, production, finance, costs, and of course design. At the very least, in preparing the case, he will need to consult his executives in the fields of finance, production, sales, and design. These men are specialists. Probably they have professional qualifications. Almost certainly they will have peculiarities of personality and temperament that have led them to their choices of profession and to their careers. Each will have his own jargon. 'Development' means one thing to the product designer, another to the production engineer, and something different again to the salesman. (The sheet metal worker also uses the word, in a fourth and entirely different sense.) So each time these men speak to each other they may easily be misunderstood. The words have different meanings, and communication is inefficient.

Application of Information Theory

In discussing engineering communications, ROSENSTEIN, RATHBONE and SCHNEERER (1964) introduce the jargon of information theory, by writing of signals and noise. For efficient communication the signal-to-noise ratio must be high. Noise arises in many ways: when, for example, a salesman talks to a designer, the original message is in the salesman's head. To communicate, he must first encode his message into words, then he must speak the words, then the designer must hear the words, and finally he must decode them in order to receive the message. But if, as is usual, the designer and the salesman use the same words in different senses as part of their professional jargons, there will be misunderstanding of the kind described by these authors as semantic noise. There may well be mechanical noise also, if the conversation takes place over a bad telephone line, or in a noisy room. And because the salesman and the designer have strikingly different personality characteristics, there is likely to be psychological noise as well.

One method of increasing the efficiency of communication, that is, of reducing the confusing effects of noise, is to introduce redundancy into the signal. In ordinary written communication redundancy is always employed as a means of reducing the effects of mechanical noise. The details of the letters now before the reader are much more complex than is necessary to distinguish one letter from another. There are many differences in the forms of letters, although five pairs only of different features would be sufficient for an alphabet of thirty-one letters. Moreover in any one language certain patterns of letter combination are common, and other patterns are rare or absent. Consequently, even in a badly written communication, the letters can usually be identified from some feature of the distorted or debased form, or from the context. However, in commercial shorthand, writing speed is achieved by the elimination of redundancies of form, and by the elimination of some letters, with the result that badly written shorthand is often completely illegible.

In an analogous fashion, when one man speaks to another in a noisy situation, he may communicate successfully by repeating his message several times. If the noise varies randomly in quality and intensity it is likely that in successive transmissions different words will be received, the others being masked by noise; after several transmissions the receiver will be able to reconstruct the entire message.

The confusing effects of semantic noise may likewise be minimized by repetition, but for success the message must be recoded each time into different words. The receiver in his decoding will then search for the meaning which is common to all the varied signals. This method can also deal with the mechanical noise arising from a strong regional or foreign accent.

Another method of reducing the effect of noise is by feedback. Thus over a bad telephone line, the receiver replies to the message by saying: 'I cannot hear you; will you speak louder.' If this fails, the original transmitter may introduce redundancy by spelling out the key words, letter by letter. He may introduce even more redundancy by using the A for Able, V for Victor system of identifying the letters. (Devotees of Hilaire Belloc should be warned, however, that such redundancies as F for Vescence, M for Sis and X for Breakfast are more likely to confuse. The only acceptable Belloc forms are L for Leather and T for Two.)

Feedback can also deal with semantic noise. The receiver may reply to the message by saying, for example: 'What do you mean by "efficiency"?' The transmitter may then define 'efficiency' in words, dictionary fashion, or he may explain it by an example, or he may repeat his message, encoding it so as to avoid the confusing word.

Feedback is particularly good for reducing psychological noise, especially when the communication is between two speakers face to face. Then the feedback signal need not be in the form of speech. The designer may be discussing working tolerances with a production man. He is saying: 'When it comes to limits I don't see what the pro. . .' and at this point he notices that the production man has become very red in the face, and that his mouth is moving in such a way as to suggest that if he could find the right words he would make a very angry speech. So the designer changes his message quickly, and encodes it in such words that he can continue without a break in transmission: '. . .blem is if we have a look at the design together to see where it can be eased.'

There are always psychological problems, because each specialist assigns most value to those features of the design which most closely affect him; the designer with performance and appearance, the production man with ease of production, the salesman with sales resistance, the accountant with costs. Under pressure, which is the normal commercial situation, everyone wonders why the other fellow makes such heavy weather of his particular aspect.

The specialists at executive level must agree upon a design project or, at the worst, the chief executive must make a decision which will make sense in terms of all the specialized information and points of view which will be presented to him. If his decision is to be a good one (and in this situation there is unlikely to be a uniquely correct one) he must be as sure as he can that he has got the message, that he has correctly understood all the signals that he has received.

This is likely to occur only if he has frequent talks with each of his executives, in which there will be much redundancy and feedback. Further, in order better to assess the influence which each specialist contribution has upon the others, and therefore upon the final decision, there must be much discussion between the specialists. In some organizations this process is formalized by setting up a development committee, or a new products committee, whose members no doubt complain bitterly of the waste of time in committee meetings. But so far, no-one has found a more efficient way of dealing with the mechanical, semantic and psychological noise that comes from human variability and human imperfection. The committee meeting provides the opportunity for verbal and visual communication in circumstances which permit maximum feedback and controlled redundancy.

The Design Team

At the functional level of design, similar problems occur, even when the product does not require a large staff. A common problem is to reconcile the requirements of the artist and the engineers in the design of a consumer durable product. Sometimes the industrial artist is a consultant, called in to 'tart up' an engineer's design. These are the works, and can he put a respectable overcoat on them? Don't bother about the gears and levers; only our back-room boys understand what they do. Just make it look pretty. Ideally the artist should refuse such a commission, but he may be short of clients. In another organization, more conscious of the sales importance of appearance, the artist may be asked for a design, and then the engineers sweat to get the works inside the stylist's form. Both of these are almost certain methods of getting very bad designs. The only way that has been found of integrating technical and aesthetic requirements in a design is to let the engineers and the artists spend enough time together for their various criteria and constraints to be mutually understood, or at least respected. Again, in some organizations this situation has been formalized by setting up design teams jointly responsible for the entire design. Thus the team for a domestic appliance might consist of an industrial artist, a development engineer, and a production engineer. They will spend a great deal of time in talking, and in scribbling on each others sketches. How else can they do their job?

Communication between Management and Design

There remains the question of communication between management and the design function. It might be argued that since the design executive is a party to any management decisions, he should fully understand what is needed, and he can therefore pass any necessary instructions to his staff. This might be true if the management decision could be drawn, so to speak, out of the air of the committee room, and if the design executive could be trusted to communicate the design decision without noise or distortion. Since no-one concerned is superhuman, neither condition is satisfied.

The new design often starts in the vaguest fashion: 'If only we could. . . .' 'I sortathought we might. . . .' It may even start with confusion concealed behind apparent explicitness: 'Something like Bodwin's pencil sharpener only for cleaning windows.' There is a stage at which the management team needs some help in visualizing its nebulous ideas. This is the stage at which there can be some profitable two-way communication between management and the design function. Communication downwards is likely to be made through the design executive. He will not rely purely upon words for this. He will almost certainly supplement the conversations with his designers with sketches, and the doodles he has made in committee. The designers and the modelmakers will prepare drawings and models based on this information.

The nature of the models will depend upon the nature of the management problem. If it is a question of appearance, the models will be quite crude wooden boxes, beautifully moulded and painted on the 'show' sides to give a lifelike impression of the product as it is conceived at that stage. If the problems are technical, the model may be a 'breadboard' model or its non-electronic equivalent. If the problems are ergonomic, the model may incorporate both technical and appearance features, especially those related to controls and the display of information.

Thus the designers can now communicate upwards to management. The communication will be largely visual, the signals being in the form of models or drawings. Some communications will be expressed numerically as predictions of performance or as cost estimates. Some communication may be tactile or kinaesthetic, when the models are handled. The efficiency of communication through these channels may be improved by redundancy in the form of verbal explanation and argument. With argument comes feedback, which will be helpful so long as it is controlled to reduce psychological noise and not to create it. Out of this variety of communication should come understanding. If the designers can be present with their executive in the development committee during the presentation and discussion of the models they will come to understand what management wants. Equally, in a typical situation, management may come to understand why it cannot have what it wants. If the ideas of management are nebulous to begin with, they will become more definite in the presence of a physical model based upon their first thoughts. Ultimately, management will become sufficiently confident to authorize full-scale design activity. Ideally it should issue a new product specification to define the design activity. This document should state precisely what sort of new product is required, what features are essential, how much it may cost, what rate of sale is expected, and how much time may be allowed to complete the design and to prepare the tools and other production equipment. This last item, together with the sales forecast, will also be needed to permit the planning and programming of advertising campaigns, negotiation of customer approval of design, purchasing of raw materials, and so on.

Given this formal statement, design may proceed as a purely functional activity. In the absence of the new product specification, as for example during the period when management is developing its own ideas, the designers must operate within their own function as best they may. As stated above, when widely different skills are involved, the best way seems to be to let the different practitioners work together, and especially talk together. In the absence of much repetitive, redundant, argumentative conversation, the artist, the technologist and the production engineer will never understand each other sufficiently to evolve integrated designs. Indeed they may not achieve even decent compromise solutions. By an integrated design is meant one in which the problems of appearance, performance and cost have been solved simultaneously in a way that is better than any individual specialist solution.

The converse situation is only too well known. Designers are often guilty of assuming that their particular expertise is merely common knowledge, and that it is not necessary to explain their problems or their solutions to the members of other functions, or to management. Production engineers, salesmen and even managers assume that their special difficulties are so well known, that the designers must know about them without being told. Others adopt the attitude that there is no point in telling the designers anyway; that designers are impervious to ideas from outside their own coterie. A great deal of the study of *The Management of Innovation* by BURNS and STALKER is devoted to recording the views of many workers in design and development, and in various aspects of management. These reported conversations have a painfully familiar ring· stories of errors and misunderstandings arising from failures of communication.

Burns and Stalker demonstrate, as a matter of observed fact, that those organizations which succeed in exploiting design and innovation are those in which the pattern of organization is organic rather than mechanistic. They list eleven characteristics of organic systems, of which two are especially relevant to this chapter:

(1) The adjustment and continual redefinition of individual tasks through interaction with others.

(2) A lateral rather than a vertical direction of communication through the organization, and communication between people of different rank resembling consultation rather than command.

These two, and to a lesser extent the other characteristics described by Burns and Stalker, support the contention of this chapter: namely, that for efficient design it is necessary to have efficient communication between all the people concerned in design, and at the management level this means the heads of all functions. Further, for efficient communication it is necessary to introduce a great deal of redundancy and feedback in order to increase the signal-to-noise ratio to an acceptable level.

Elsewhere, (BUCK, 1963) I have come to the same conclusion by examining the operation of a perfectly bureaucratic model organization in which a new product is being designed. The organization pattern of the model is taken from actual examples in industry with which I am familiar. In the model, design and production are controlled by executives responsible to the general manager; but two aspects of design – model-making and production engineering – are controlled by the production executive. This is quite logical since the model-makers need a workshop and the production executive controls all workshops. Without control of production engineering, the production executive cannot control production, so the design executive has direct control only of the designers and the development engineers. The only theoretical feature of the model is that communication is rigidly confined to the channels of authority. Consequently, every doubt or query raised by the model-makers when the prototype is under construction has to be referred, in turn, to the foreman, the production executive, and the design executive, before it reaches the designer who can deal with the problem. The same long chain is involved each time a development engineer requires the prototype to be modified to remedy a fault, and each time a production engineer wishes to change the design to reduce costs. Clearly, in this model any foreseeable market would be lost long before the design could be completed.

Conclusion

The quality of design decisions at all levels is likely to be greatly improved and expedited by the active encouragement of free communication between all those people involved in design, both at management level and within the design function. The problems are familiar to designers, though possibly not so obvious to people in other functions in industry. Now that they have been fully documented by Burns and Stalker no-one has any excuse for shirking the problems of communication in design. Three actions seem to be necessary:

(1) Managers and designers should devise means for improving communications within their organizations and departments.

(2) They should attempt, either by their own efforts or by enlisting the help of social scientists, to assess the effects of the changes on the validity of their design decisions, on the speed with which these decisions are reached, and on the morale and profitability of their organizations.

(3) They should publish their results for the active help and encouragement of all.

Finally, it is suggested that when design is revolutionary rather than evolutionary, communication may prove to be the most intractable problem of all. For, in order to attract financial support and technical assistance, it is necessary to communicate the new idea to those who have not yet seen the light. In this situation semantic and psychological noise will effectively mask any orthodox signal, and effective communication will require even more preparation and more patience, more explanation and more argument – simply, more redundancy than in our rather workaday example.

Chapter 31

DESIGN, MANAGEMENT, REALIZATION AND CHANGE

S.A. Gregory

Introduction

Much of the discussion in this book has been directed to specific aspects of design, to design as a process and to techniques and principles contributing to the execution of particular stages in design. Chapter 27 has devoted necessary attention to the way in which design operates as an important and critical function of a manufacturing company, and to the way in which the design system fits into the company organization and participates in its activities, nourishing and being nourished by them.

The present chapter is concerned with the practical consequences of the fact that design is a process. It prepares the way for a detailed study of the technical basis which underlies the relation between management structure and technology developed by WOODWARD (1965).

Steady-state and Unsteady-state Processes

One tends to think of much of design as contributing to a broad stream which carries on in a substantially unchanged flow, and in which the individual effect is almost unnoticeable. This continuous and steady flow is one's image of the industrial process and of the economy as a whole. No doubt, this image provides some comfort, because it reflects a kind of stability and because it is an easier situation to deal with than one in which major variations occur. Furthermore, the steady-state view tends to accord better with British national outlook on industry.

However, taking either a long perspective, such as that of TOYNBEE (1960) who sees the rise and fall of civilizations, or looking only at the activities involved in the design of one small product, it is an unsteady-state process which is observed. This unsteady situation may be comparable to a ripple on a stream, or to the growth and decay of a plant. In either case there is now to hand substantial formal theory and techniques to deal with such situations.

At one extreme, there might be a relatively stable manufacturing organization, apparently in balance with its market. The company structure is almost certain to comprise vertical functional divisions of the classical 'mechanical' type, embedded, as in a fossil, in the description of organization by BRECH (1957). For some reason beyond the management's control a change has to be brought about, either in the design of one product which contributes to the stream of output, or in the effectiveness of the design function. The method of design associated with product improvement will be only too familiar by now. The improvement in design office effectiveness may come from improvement in individual designers by training, which might be, for example along lines suggested in Chapter 21. Or it might come from an analysis and reallocation of tasks in the design office using the techniques of work-study, as outlined by CURRIE (1960). TURNER (1964) has studied the activity of a drawing office, and an introductory statement on the application of work-study to a design organization has been made by FEARN (1962). Others have examined aspects of control through costs, including network methods. The rather less immediately effective changes in overall policy or in the environment and atmosphere have been discussed in Chapters 28 and 29.

The implementation of such changes may be seen as a disturbance, and handled in terms of industrial dynamics, as developed by FORRESTER (1961). The detailed planning may be executed by a suitable network technique.

On the large scale, the introduction of a new design may be radical and critical. It may represent the embodiment of a substantial change in direction or rate of growth of a social group, or it may be the production and use of a new supersystem; in some cases it may concern a complex of such things. Obvious examples are the USA space programme; the UK National Plan; the development of a non-industrialized country.

Such phenomena, whether large or small, may be considered in terms of individual item growth and in terms of the comprehensive social or group growth. As far as the individual item is concerned, a suitable sequence of comment seems to be: the birth, growth and death of a product; the project management of a complex one-off product, including management structure and techniques; the interrelationship of marketing, research, design, manufacture, utilization and financial operations.

The Life-cycle of a Product

The life-cycle of a product is largely determined by the organization which produces it, and by the environment into which it goes. The necessary 'profile' of a proposed new product, which recognizes the need to fit the production organization and the environment, has been outlined by HARRIS (1961). It is such a profile and its fit which may exercise the dominating factors in investment appraisal, rather than any single criterion approach, as has been suggested on the basis of empirical studies by WILLIAMS and SCOTT (1965). Indeed, such investment criteria as those which employ discounting to the present date, with allowance for estimating cash flows for individual years during the life of the product, include in principle the possibility of making an adequate financial appraisal. It is most likely, however, that the life-cycle of the product will be incorrectly foreseen.

Some of the difficulty in estimating lies intrinsically in the uncertainty of the future. On the other hand, more needs to be generally known about the life-cycle patterns of products, empirically and theoretically.

A number of phenomenological observations have been collected by BRIGHT (1964) but it cannot yet be said that there is information about enough projects in sufficient detail. NORDEN (1963) has provided details of empirically based equations dealing with growth. The development of the field of industrial dynamics by Forrester and, in particular, its application to the elaboration of new products by ROBERTS (1964) provides a technique which, although suggesting possibilities, probably substantially outruns information.

Certainly the most detailed practical attempts at growth analysis have been made by the people concerned with project management, particularly using the new network planning techniques.

Project Management

Those with experience of new product design and development are keenly aware of the difference between the management's needs to get the product established and the traditional management structure recommendations. This difference is felt most acutely in organizations which have a large content of established lines. HALL (1962) discusses alternative methods of organization for 'mixed' operations in a concern with substantial new system projects. He differentiates between the departmental form of organization and the task-force arrangement. Students of management will recognize the various synonyms for such structures. Project management is essentially the kind of management set up to deal with situations of change, and is the most common version of the task-force system.

Project management has probably been developed to greatest effect in organizations whose concern is solely with new projects, *i.e.* in firms which deal solely with large one-off contracts, or in the special branches of large user organizations set up to deal with new projects.

BAKER (1962) summarized his diversified experience within large user organizations in a mechanical and largely unperceptive manner. This was at a time when the Americans were gathering to boil down their experience in dealing with military projects, as brought together by KAST and ROSENZWEIG (1963). Comparable, but earlier experience in Great Britain is given by POSTAN, HAY and SCOTT (1965).

The organizational procedures in a general sense are the same in any of the major plant contracting organizations. They have become almost commonplace but there is, as yet, no readily available comprehensive work on the subject. Numerous papers have been given but not recorded. The joint institution symposium of 1966 marks a change.

Project Planning by Network

In addition to the increased awareness of the techniques of search for market opportunities, economic and technical, perhaps the greatest influence in project management has come from the development of network techniques.

The move from the older planning methods, using the Gantt chart and similar devices, began in 1956–1957. The earliest work came from studies of possible applications of new management techniques to the engineering functions of the American chemical manufacturing company, E.I. duPont de Nemours. The first studies concerned plant overhaul and similar work was being undertaken by the C.E.G.B. in Great Britain. The USA work gave rise to the CPM (critical path method) and details of the growth are given by O'BRIEN (1965), a member of the consulting organization which spread the early use of CPM. Much greater prominence was achieved in its early years by the allied technique – PERT (programme evaluation and review technique). This was developed for the US Navy ballistic missile project and its points have been competently summarized in a short article by the firm of consultants associated with it (Harvard Casebooks, 1964).

The initial network planning and control techniques, although having certain points of difference whose significance is now receding, depended upon the production of charts consisting of points (nodes) which represented events, and interconnecting lines which represented activities. Some quantity such as time might be attributed to an activity. By setting out the complete network from start to finish, it became possible, by working from the 'finish' end, to determine which path from a number of contemporaneous activities constituted the critical path. In the light of this information certain actions might be undertaken.

A useful introduction to this method of planning and control is provided by LOCKYER (1964) who makes clear some of the extra values that come from its practice. It provides a discipline which forces consideration of what has to be done, when, by whom, and in what order. It makes clear what decisions have to be taken and provides the basis for indicating the decision-maker and some consequences which may flow from his decisions.

The construction of the network is essentially a specialized design operation. A sequence of future events is projected in the light of current knowledge of realization facilities, and is selected to provide what appears to be an optimum pattern.

The initial development of network planning techniques was concerned with the problem of achieving a desired completion date. The PERT method introduced the notion of dealing with uncertainties. Today, as a result of many diverse investigations, network techniques may be applied to other aspects of projects than time or completion control. For example, it is now possible to prepare network plans in which account is taken of restrictions in availability of resources. These resources may be any of those commonly used, namely men, machines, money, in addition to the previously considered time. Readily available books on these wider issues are those of MODER and PHILLIPS (1964) which deals particularly with cost and with statistical aspects of PERT; and of WOODGATE (1964) which covers a wider range of applications against a computer background.

Today, the more generalized approach and the study of situations involving interrelated programmes are seen.

Interrelated Programmes

Within a single project, situations exist where some events have to occur before others, or where, in the case of parallel activities and limited resources, decisions have to be reached and implemented regarding priorities. Such situations may exist on the level of the supersystem, or in a developing country, or in an industrialized country preparing a substantial change in economic activity.

A qualitative discussion of interactions in the evolutionary growth of complex systems is given by SALZER (1961), indicating possible ways of avoiding development of everything at one step. This concept of permitting growth of individual parts of a newly developing economic system, with phasing-in of different stages across the whole economy, has been outlined by SZUPROWICZ (1963).

Within a developed economy, such as in Great Britain, the interconnections of various branches of the productive system are extremely complex. In spite of this it has been possible to build up computer models of the economy. STONE (1965) and his colleagues at Cambridge have particularly developed this approach. In their economic matrices they display alternative patterns of products from a given economy with certain resources at any period in time. SHONE (1965) discusses how it is possible to develop a succession of these matrices against time, setting out preferred lines of development of individual industries in some detail. This kind of projection demands, of course, some general agreement on possible optimizing criteria for such operations.

Within any company, the interrelations of activities over time in connection with company growth are exceedingly complex. However, the various topics touched upon in this chapter are beginning to promise possible ways of analysis to help towards dealing with such problems, particularly the interlinking of research, development, design, production and sales.

More General Approaches

The past few years have seen the generalization of thinking about networks. For example, activities have become nodes and events have been displaced to arrows, thus inverting the original planning network mode of indication, although becoming more intelligible to all those engineers who expose the technical circuits of their processes in the latter way. Much more general still is the development of the mathematics of networks and its drawing together from the most diverse of fields. ELMAGHRABY (1964) has developed an algebra for generalized activity networks.

It has now become possible to look at the decision problems within the whole field of technical development in some kind of rational way. Given the restrictions in the expression of some objective function by which to express the desirability of a proposed investment of resources, as discussed in Chapter 10, the problems of decision in successive stages of the total scheme may be investigated. It is possible to start with the idea of dealing with a portfolio of investments, as developed by ADELSON (1965); the most promising portfolio of research prospects can then be selected, according to the pattern suggested by DAVIES (1962). The course of an individual research project may be plotted out. In quite comparable fashion, the course of any project may be plotted out from the state at which sufficient data have been established to the completion of the construction of the production plant, making due allowance for loss of opportunity owing to the need for constructing pilot plants along the way. This has been worked out by Gravenor, but has not yet been published. In his procedure the set of alternative trees is drawn out against time. Money values are given to markets for individual years, costs of pilot plants and full-scale plants are provided, and probabilities are accorded to alternative outcomes at various stages along the routes. Starting from the finishing end, each tree is summed in order to find the best decision at the furthest nodes and the system is gradually 'rolled back'. Once the preferred route has been reached, another network planning operation can then be started, including within its scope both design and pilot plant investigation, gradually leading to final design, fabrication, erection, testing and commissioning.

Although this all sounds fine and rather deterministic, it is in fact highly uncertain. Any decision criterion used in an Adelson procedure suffers from its considerable simplification of the full needs of the new product profile of Harris. Furthermore, the Adelson procedure makes no allowance for the expected relative value function as defined by FISHBURN (1964), of the particular company directors, or of the social system as a whole. Any choice of a portfolio of research possibilities relies upon some estimate of the likelihood of success, which, in the last analysis, will be subjective. Similarly the planning of any research project is likely to be extremely tentative, and its execution will be replete with heuristic decisions. In any case, no research should be undertaken until some exploratory evaluative design has been carried through, in order to set the result in a possible practical perspective. Any tentative design will, by obligation, necessitate strings of decisions in uncertainty. Having gradually worked through the research and development stages, expending limited resources on those aspects of the proposed design where the greatest uncertainty prevails, suitably expressed in expected relative values, the planning of the final scheme is reached. In this part of the network, those features are put down which appear to be significant. The best use of available resources are evaluated by procedures which are largely heuristic, *i.e.* taken in the light of the particular state of affairs. People are attempting to make some of this more routine, by the study of possible strategies for particular objectives. It must be recognized that these strategies have no absolute rules stating when they should be used. A simple introduction to research planning and heuristics comes from RHENMAN (1964) who advocates further study of practical situations.

Conclusion

A substantial, growing, and justified amount of study is being devoted to the improvement of project design and management. Techniques and analytical procedures have been developed which cover much of the field. Although some of these models lend themselves to application at specific points, their use must be based on judgment; judgment lies indeed within their use.

In all practical situations, resources provide limitations. All the overt and rational procedures, which the labours of devoted people have made available, cannot be used. One cannot afford to go through the detailed operations: jumps must be made. It is here that skill, experience, and courage, show to the world who are the true designers and the true managers. It is in the regions just discussed – in the ability to distinguish almost instinctively between the trivial and the significant, with relevance to some broader strategy, in an appositely heuristic manner – that the skills of manager and designer come close together.

Much of lower management work consists of the operation of systems already planned and constructed by others. Prescribed procedures exist for the motivation and control of the operators working within the system. Such a manager has the duty to sense situations in which major change may occur and to prevent such change from happening. The greatest challenge comes from the obligation and opportunity to improve operations. It is to assist the rational development of such activities that work-study has been brought forward to deal with smaller problems, and operations research to deal with larger problems. But they start largely on the basis of an existing situation and with existing resources committed. Many designers work within such situations of limited change. They deal with the minor re-organization of material resources. The corresponding managers modify the deployment of human resources and the allocation of individual responsibilities. Each may be answerable to some specialist division.

In the evolution of new projects, design and management become closely interrelated. The designer, the planner and the manager each suggest possibilities: between them, by close discussion of the critical points, agreement is reached within suitably defined terms of reference. The difficulties of planning may be solved by the creative labours of the designer; the difficulties of design may be settled by the imaginative response of the manager. Where one role rather than another should act as co-ordinator is a point of difficulty and hints about tackling it have been given by HIGGIN and JESSOP (1965).

Within such a relationship of interaction and response, the new models of procedure facilitate action: they help to prevent the growth of unnecessary tensions; they indicate responsibilities. In Chapter 2, McCrory has pointed out the advantages that come within an organization from a recognition of the requirements of the execution of the design method (task diagram for technical planning programme). The manager knows his responsibility to any part of the scheme. Such parts of the scheme may, themselves, be set out in terms of suitable networks, whether dealing with marketing, research, or other factors. Reference has been made to the range of models available.

Such models are essentially for planning and co-ordination. Decision models within them are as applicable to the designer as to the manager. All models, in the terms of Chapter 17, are very likely to be highly simplified and this simplification must be continually remembered.

The networks and trees represent the most detailed model of the planning process that the human mind has been able to achieve. They provide a rational co-ordinative discipline of anastomosis and yet carry within themselves the constant possibility of change, creative endeavour and heuristic decision. Although they were developed for planning they give the best models of the design process itself. It is against such models that design science will grow.

PART VI

DESIGN RESEARCH

Chapter 32

DESIGN METHODS REVIEWED

J. C. Jones

Introduction

The first British conference on design methods was held at Imperial College in 1962. Eighteen contributors from engineering, architecture, planning, building, industrial design, graphics, painting, psychology and cybernetics proposed some new methods of designing and offered many descriptions of the design process (JONES and THORNLEY, 1963). In reviewing these and other papers, I have tried to map out and discuss the design situation as a whole.

Definition of Design

It is not always easy to tell what is meant by the word design. O'DOHERTY (1963) points out that it has been used to mean:

A visual or tactile shape.
A plan or 'conceptual creation'.
The end-product (of such a plan).
The purpose, intention or motivation (of the planner).
The governing or controlling of a process (of cybernetic exploration).
A symbol or a set of symbolic representations.

He concludes that a term which is used in so many different senses is empty of content. He suggests that its vagueness comes of a confusion between sensory-motor skill (which enables one to wield a pencil), 'phantasmal' capacity (which enables one to envisage detailed mental pictures of things that do not yet exist), and conceptual capacity (which enables one to form a general plan to which one can confidently commit oneself and one's resources before the plan has been imagined or explored in detail). O'Doherty's own use of the word design is in the limited sense of 'the production of conceptual structures' such as drawings, blueprints, *etc.* He distinguishes between the generalized, reproducible end-product of the design process and the specific, unique, non-reproducible end-product of the process of art; he suggests that a scientist and a designer work from the particular to the general whereas an artist works from the general to the particular. There is another such distinction which I would like to make: between a scientist's generalized description, which he hopes is true for all members of a class of things that exist, and a designer's generalized description, which he hopes is true for a new class of things which do not yet exist but which can be made from that which exists.

RESWICK (1965) has emphasized this view in his definition of designing as a 'creative activity – it involves bringing into being something new and useful that has not existed previously'. ASIMOW (1962), in seeing engineering design as the production of a 'model which is used as a template for replicating the particular good or service as many times as required', agrees with O'Doherty. BOOKER (1964), in a similar description of design 'simulating what we want to make (or do) before we make (or do) it as many times as may be necessary to feel confident in the final result', emphasizes modelling and repetition to reduce uncertainty rather than to make copies of the product. ESHERICK (1963) in his arguments against too much determinism in the design of regions and buildings, distinguishes between *(i)* a scientist's neutral explanations of past events, and *(ii)* a de-

signer's committed actions which set off endless and unpredictable trains of events into the future.
Asimow defines designing as 'decision-making in the face of uncertainty and with high penalties for error'. MANN (1963) discusses the inherent difficulty of designing and gives the example of a military aircraft which has more than ten thousand parts. All these parts must satisfy their functions, must be compatible with one another, must be adequately strong and yet of minimum weight and volume. MATCHETT (1963) in his definition of a 'good' design emphasizes the need to integrate a mass of potentially conflicting and possibly misunderstood requirements into a satisfactory whole. This he calls 'the optimum solution to the sum of the true needs of a particular set of circumstances'.

It should be noticed that neither this definition, nor any of the others quoted, implies that good designing is measured by any absolute qualities of the final product. The general view is that the quality of a designed product is measured by its performance, *i.e.* by its relationship to the situation in which it is to be used and seen.

Design Situations

It is probably a mistake to equate designing with problem-solving. It is more like 'problem-finding' which has been discussed at length by MACKWORTH (1964). The situations with which designers of various kinds are faced are less clear than the problems that arise in games like chess or in examination questions. Asimow states: 'The designer is presented, not with a problem, but with a problem situation. . . . it is out of this milieu of perplexity that clear definitions of the relevant problems must be drawn.' Not only has the designer to find problems which he hopes will prove to be relevant, but he has to envisage the performance, shape and manufacture of an (as yet) non-existent product and predict how it will influence, and be influenced by, the original design situation. It seems that designing is not so much the solving of a set problem as the performing of a very complicated act of faith.

Limitations

There are limitations which are common to many kinds of designing. First, there is never time to collect and assimilate more that a part of the relevant information or to perform more than an incomplete and oversimplified analysis (Mann). Second, there is the difficulty of spotting errors before the design is well advanced. Third, there is the high cost of altering or abandoning designs upon which much time has been spent. As was pointed out by PAGE (1963), the designer has to 'optimize the design, optimize the design time and optimize the design costs. . . . Rapidity is vital but this must not be bought at the expense of performance.' He suggests a strategy of spending as much time as possible on analysis and evaluation, both of which are cumulative and convergent, and of minimizing non-cumulative time spent on the synthesis of a single solution which may turn out to be a dud. Several alternative solutions should be developed in parallel, but not in detail, until clear evidence of the convergence of one acceptable solution is obtained.

The aims of the systematic methods discussed later are to increase the chances of adopting Page's strategy and to make it less necessary to develop bad designs in order to learn how to develop good ones. The common feature of these methods is to formalize and make public the designer's thinking in the early stages. Thus more design effort can be applied at the beginning, when it is most helpful, and less towards the end, when it can be wasted.

Complexity

It seems that all design situations are complicated no matter how simple or insignificant is the thing that is designed. ALEXANDER (1964) has discussed the complex patterns of user requirements, manufacturing requirements and physical configurations that lie behind such apparently simple shapes as a kettle or an Indian village. STURT (1923) gives some of the reasons for the tilting and curving of each part of an English farm wagon and describes the consequent 'interaction of its parts'. His views support Alexander's thesis that a design achieves stability and perfection when the visible structure of its parts is adjusted throughout to the invisible structures of the situations in which it is to be made and used. The modern design situation differs from traditional ones in that requirements, materials and manufacturing resources change very much more quickly than they did. New design situations constantly appear, and existing design situations tend to change faster than does people's ability to design products in which these changes are properly reflected. This recent increase in pace has not been matched by the widespread adoption of faster methods of designing.

Four Kinds of Design Situation

It is useful to distinguish between four kinds of design situation, as follows.

Environment – The designing of regional plans and of buildings is intended to provide a 'strategic framework in which other people can operate in detail', or enclosures 'which man inhabits as a biological species' in an 'evolutionary situation over which the designer has no final control' (Page). In this kind of design situation, the design costs have to be recovered from a single item and no prototype is possible. The criterion of success is adaptability to changing circumstances which it is not feasible to anticipate in detail and not desirable to limit by an over-structured design.

Flow Systems – These are sets of separate components which together perform a well-defined function Examples are: a missile detection system, an airline, an administrative system, a supermarket or a telephone system; on a smaller scale, the combination of washer, drier, iron, ironing board and airing cupboard which together comprise a not very coherent system for removing the marks of use from clothes. Flow system design includes the specification and positioning of components to perform a function, but does not include the designing of components. Provided the system has a recognizable throughput, and provided that the throughput is not greatly affected by the physical (as opposed to the sequential) disposition of components, the flow diagrams and related calculations of system engineering can be applied to predict performance with reasonable certainty, however large the system may be (GOSLING, 1963). It seems that there is much to be gained by using these techniques outside the military and space-exploration fields in which they have been applied with astonishing success, for instance Polaris, Telstar, Early Bird, man-in-space.

Products (or Mechanical Systems) – A product or mechanical system is a single unit of closely integrated parts which together perform a set of functions. It may be a component in a flow system or in an environment, or it may be used independently, for example a window, a tractor, a garment, a telephone, a pump, or a tube of toothpaste. The significant thing about product design is complicated detail. Both the performance and the cost of such a product are very sensitive to small changes in the physical disposition of its parts. This difficult design situation requires very great design effort in proportion to the cost of a single product. In the past, this effort was spread over a long period, perhaps centuries, of evolution by trial and error. If, as is increasingly the case, there is no time for slow evolution, the design effort has to be paid for by making large numbers of identical products in a short time. The problem then is to simulate the trial and error process using drawings, models, tests, calculations and the experience of designers, before the necessarily high tooling costs are incurred.

Parts – These are single pieces of material from which products are assembled. A part is usually designed specially for a particular product, because of the high degree of interdependence that is required between parts if product performance is to be achieved without high penalties in cost, weight and size. In such cases the requirements which each part has to fulfil are more easily discovered than are the requirements of the product as a whole. Less often, standardized parts such as nuts, bolts, tyres, knobs, pipes, bricks, and the like are designed for situations which recur or when interchangeability is required. In these cases it is very difficult to discover the requirements which will have to be satisfied. The difficulties of achieving variety reduction and of getting agreement for standard dimensions, probably reflect the unwillingness of designers to reduce their room for manoeuvre by the incorporation of standardized parts, however cheap these may be.

Changes in These Situations

The present interest in design methods would surely not have arisen if the above four kinds of design situation, each of which has existed for a long time, were not subjected to some recent and rather sudden changes. What changes can be perceived?

In the case of environment, there is a general and rapid increase in the scale of road traffic and in the rate of building. These new demands cannot be satisfied without new facilities such as motorways and industrialized building. Also needed are new restraints such as pedestrian segregation, traffic guidance systems, dimensional co-ordination of building components, and better environmental standards. Each of these developments calls for much wider and more exact knowledge than is available within the experience of any one designer, or design profession, and demands new techniques by which to anticipate the ways in which new and old features of the environment will influence one another.

In the category of flow systems, there is growth in the size of organizations and communities and greater competition between systems of transport, mass entertainment, education, military defence, retail distribution, and so on. Ahead, there is the need to radically alter the present codes of professional conduct and practice as the activities of engineers, teachers, doctors, shopkeepers, clerks, machinists, lawyers, accountants, dustmen, telephonists, pilots, typists, travel agents and many other professionals are partly assigned to such machine components as computer networks and television links. Rethinking the human or 'software' aspects of the organized man–machine systems that are emerging in these areas, is often a greater design challenge than is the design of the 'hardware' components. The largest single difficulty is, however, the absence of criteria and methods for dealing with these emerging man–machine systems as a whole and in relation to each other.

The design of products, although a field in which there is a long tradition of good design, is at present the cause of failure and anxiety (Feilden Report, 1963). There appear to be two sources of difficulty. First, some of the talented people who in the past became engineering designers are now able to enter occupations which are more highly rewarded and esteemed: there is left a need to systematize detailed work so that it can be done by persons of less talent or experience. Second, there is the growing complexity of products and their integration into more closely knit systems. This demands of each product greater reliability, greater compatibility with other products, and greater certainty that it can be sold in increasing quantities to increasingly diverse and discriminating customers. These new demands are being satisfied, at least in part, by the appearance of new kinds of design specialist, each of whom is concerned only with one aspect of designing, such as reliability, quality, optimization, appearance, ergonomics, cost reduction, system compatibility, environmental testing and so on. These new kinds of engineers and designers (design technologists as they are starting to be called in Manchester) require means of formalizing the design process so that their contributions can be given their proper place. Formal design methods should also help the general practitioner designer, who in the past dealt adequately with all aspects of one design by himself. He now needs a means of meeting the new specialists on their own terms, so that his central position can be recognized and so that he can make proper use of specialist help at the right time instead of treating it as unwelcome interference which he puts off seeking as long as possible.

Within the class of engineering products there appears recently to have been a greater proportion of devices for which there is no precedent, 'nouveau designs' as they are called by both Asimow and Mann. Examples are satellites, prosthetic devices and nuclear reactors. The design of products in this category demands techniques of deliberate innovation which, if successful, have the valuable results of starting entirely new industry (MOULTON, 1965) and extending the scope and opportunity of human life. The formidable difficulties that have to be overcome in deliberate innovation are in assessing needs which have not hitherto existed; and in exploring simultaneously a sufficient number of alternative solutions to ensure a high probability of 'instant' operational and marketing success for the version which is chosen for the very costly processes of detailed development, production and distribution. A third difficulty is that of foreseeing novel and disconcerting weaknesses or side-effects which did not occur in the less specialized devices which the nouveau design will replace. Road accidents, jet aircraft noise near airports, and 'blacking-out' in the first monoplane fighter planes are notorious examples of such side-effects. The recent practice of measuring side-effects early in design can be inferred from the astonishing safety records of both nuclear industry and space flight, and can be seen in the attempts to measure the effects of sonic boom before the introduction of supersonic transport.

At the smaller and more detailed scale at which the product designer habitually works, there is always a host of less destructive but no less unacceptable limitations and side-effects which are likely to be overlooked in a nouveau design. There is clearly a need to equip product designers with formal methods of checking for side-effects that may fall outside the experience of anyone in the design group.

The designing of special purpose parts is inseparable from the designing of the products of which they are ingredients. Standardized parts, however, introduce new problems and are in greater demand than was formally the case. Movement of people and new international agreements call for greater interchangeability of such parts as electric appliance connectors, nuts and bolts, tape spools and office stationery. The long-delayed mechanization of the building industry calls for modern equivalents of the traditional brick, which has proved so difficult to equal in its adaptability, its favourable combination of many properties and its low cost. In this kind of design problem the simplicity of the result disguises the complexity of the needs to be satisfied.

Gradual Evolution Versus Nouveau Design

Designers sometimes have a choice between the gradual evolution of an existing product and the sudden introduction of a nouveau design. Consider the early Whittle jet engine and the highly developed turbo-supercharged Wright Duplex Cyclone radial engines which used some exhaust gas thrust. Consider also the prop-jets of the 1950's. It can be seen that not only are there marked physical similarities between the late versions of a traditional design and the early versions of a nouveau design, but there is also an overlapping of performance levels. The major difference in the short run lies in the lower cost of gradual evolution. Only in the long run, after further development of the nouveau design as a pure jet, did a major performance difference make itself felt. In the middle run, the prop-jet might be regarded as a step backwards to get economic advantages which the pure nouveau design had not yet achieved.

Another such comparison is that between the Boeing 707 and the VC10. Is this a case of a new aircraft having insufficient advantage over a more traditional one to make its development worthwhile, or is it the reverse? It seems to be very difficult to make intelligent judgments on questions such as this, and very costly to make a misjudgment.

The Adaptability of Products to Situations

These examples suggest a promising subject for design research – a study of the evolutionary paths of man-made things. Are there some laws of artificial genesis and evolution which could be inferred from the history of engineering design? Could a knowledge of such laws permit a better choice between the many paths which lie open to the designers of a new product? What factors govern the frequent extinction and the infrequent survival of a new product or invention? Analogy with biological evolution, taxonomy and genetics suggests that there is scope here for a fundamental advance which could be of practical importance.

Presumably the factor that settles the fate of a new design is the response which it elicits from the situation into which it is thrust. This response can be such as to inhibit further development, as in the case of early gas turbine cars; or, as in the case of the jet to prop-jet sequence, the situation can induce partial return to the previous norm. Successful new designs, such as railways or digital computers, however, seem to have elicited from situations, which appeared unready to receive them, a reorganization of existing practices and attitudes that not only allowed the new product to survive but encouraged its further growth until it became a new norm. JACKSON (1964) describes how the great difficulties of getting the Volta River Project under way were overcome by keeping initial capital costs low. This involved the sacrifice of some of the project's best features, but allowed it to reach a stage when it could elicit its own support. In such a case the purpose of the product is to restructure the situation rather than to satisfy an existing demand.

Alexander has pointed out that the choice of components from which a product or environment is composed can limit its adaptability to existing situations and to unforeseen changes. He proposes the mathematical minimizing of the network of dependencies between groups of functions so that local adaptations to change can be made, without the often unacceptable penalty of having to redesign the whole system. Alexander has cast a new light on the fundamental difficulty of designing: that of choosing the components of which the product is to be made and of relating these to each other. He seems, however, to overlook the performance and cost penalties of minimizing the dependence of one component on another. It has been suggested that an aeroplane designed on this principle might be too heavy to get off the ground. Alexander's approach may be more applicable to the design of environments, or to systems of standard parts, than it is to the design of mechanical products. The designers of industrialized buildings might gain much by loosening the many dependencies between the components of a house before tooling-up for quantity production (JONES, 1965). It is interesting to see that the furniture industry is following the lead of Eames in allocating each major function of a product to a separate component. Chairs, tables and cupboards are no longer single entities but instead consist of standard body support shells, storage units and legs which can be mixed in many different ways. Customers can thus be offered many choices, and components can be made in larger quantities.

The Determination of Needs

The relationship between a product and the needs which it satisfies is two-directional. The needs to be satisfied by a nouveau design do not always exist even when the means of their satisfaction is under development, as can now be seen in the case of space vehicles and of the Concord. There must have been a time when this was true of any successful innovation such as the ball-point pen. It is also true of any unsuccessful development. Are there some needs which exist before suitable products are designed and is there any sure way of identifying the needs which a new product is capable of bringing into existence?

It is, of course, the sponsors and the users of products who ultimately decide which needs they are willing to pay to satisfy; but it is nevertheless a part of a designer's job to re-assess these needs before spending his sponsor's money on aims that may not be realistic or well chosen. A difficulty here comes of the orientation of users and sponsors to the present, and of designers to the future. It is doubtful if anybody considers a need or aim to be real unless he can envisage a means of satisfying it. Users and sponsors of design, being concerned with what already exists, will tend therefore to specify or approve of aims that can be satisfied with small departures from existing designs. They will not find it easy to believe in non-existent demands which designers, with their antipathy to the present and their power to envisage the future, claim will come into existence when the means of satisfaction becomes available. This conflict lies behind the professional designer's traditional distrust of those forms of market research which are based on the housewife's immediate reactions to new designs of which she has no experience.

One of the advantages of small organizations is the possibility of bridging this gulf of potential mistrust between sponsor and designer by close ties of friendship, family relationship or mutual respect. When this occurs, there may be no need for the checks and restraints which a more remote management feels obliged to put between designers and their interpretation of future needs. There are signs that a new profession of design management is springing up to provide this bridge in organizations where it does not already exist (FARR, 1965).

Some design theorists advocate the fixing and weighting of objectives before design analysis begins. Others, with whom I agree, believe in exploring the design situation and its possible solutions before deciding the design objectives, each of which should be assigned initially on equal value. The argument of the first group is presumably that, without clearly evaluated objectives, no progress will be made. The opposing view is that objectives that are set without knowledge of the feasible solutions are likely to restrict a designer's area of search. Furthermore, the weight which one would ascribe to an objective is a function of the solution one has in mind. If one is thinking of a Rolls Royce, one will not rate very highly the objective of easy parking. If one is thinking of a minicar, one will put parking high on the list.

A strategy which side-steps this difficulty is to have three sets of objectives, and to seek three sets of solutions. Type (1) will satisfy only the sponsor's most immediate aims and will involve the minimum modification of existing hardware and software. Type (2) will involve the assessment and satisfaction of needs which are not so pressing and are more expensive to satisfy, but which offer greater advantages to users and impose fewer constraints on the designer's search space. Type (3) will aim at the satisfaction of all new demands which could be expected to come into existence as a result of unconstrained development to the limit of the current manufacturing expertise. Initial proposals for all three types are prepared before the decision is made to go ahead with one or more of the alternative sets of objectives and possible solutions.

Designers

Recently, much has been said about potentially creative persons, but not so much about persons who have actually created something which is valued by others. GETZELS and JACKSON (1962) and others have suggested the idea that creativity can be measured by the number of unlikely uses which a person can think of for an object such as a brick or a top hat. It appears that persons who score highly in such tests are not always the most intelligent. It is pertinent to ask if successful artists, designers or inventors would select, as assistants, persons who have the greatest number of ideas; or would they look first for evidence of having created something, and second for the ability to envisage clearly the physical conditions which decide the feasibility of an idea?

Mann has drawn attention to what he calls a 'bimodal attributes' of a successful engineering designer. First he needs sound knowledge of the physical principles that are relevant to his area of work: engineering teaching has in the past been aimed at providing this knowledge. Second, he needs the ability to deal with ambiguity, incomplete knowledge and the absence of reliable theory. Both of these seemingly contradictory abilities are needed to convert an unstructural design problem into an accurate description of a physical assembly which can be relied upon to solve it. The ability to tolerate uncertainty while prolonging the search for a sufficiently reliable solution, and when committing large resources to untried ideas, is also relevant.

Mental Processes

O'Doherty give prominence to the ability of gifted persons to carry out simultaneous translations between different sensory modalities. He has also referred to the ease with which an artist can recall details of the appearance of something he saw months or years ago, whereas a layman may be unable to recall more than its general character after only a few minutes. The size and contents of the memory seem to be closely related to the level of creative achievement.

Mann describes the pattern of an engineering designer's work as long periods of routine analysis which he calls 'crank turning or grunge', relieved by 'creative peaks'. O'Doherty implies that the onset of a 'leap of insight' is by no means accidental, but is consciously induced by the undertaking of long periods of immersion in details of the problem. BELLO (1959) quotes Land as saying that for him sixty hours of continuous work on a problem is equal to a year of interrupted thought. Mackworth suggests that a person capable of originality has a capacity for 'effective surprise' at small but, to him, significant differences between expectations and reality. It may be that this surprise is what induces the leap of insight to which O'Doherty refers, and in which the more deterministic design theorists appear to disbelieve (SIMON and SIMON, 1962). O'Doherty refers to 'two camps in respect of creativity: one holds the rather Platonic mystical idea that one is visited by one's daimon and the creative act follows'. At the other extreme is the Mill tradition that 'all one has to do is to put things together and the result will be a newly created product'. The first view is implied by 'claims that one is seized by the unconscious, or by the numinosum, or by inspiration, or by the medium itself – the brush, or the pen, or the chisel, which then is supposed to guide one's hand'. The second view is implied by many theories 'which would repudiate its explicit formulation. Thus it is implied by cybernetic models of the creative process, by "brainstorming", and by logical positivist approaches.'

O'Doherty makes the point that skill, which is a constituent of the creative act, is learnt on the basis of an innate endowment. It is retained within the nervous system not as knowledge but as performance, which the skilled person cannot himself explain. He suggests that 'kinaesthetic images' (the memories of bodily sensations that accompany skilled performance in perceiving and doing) are the media through which a performer consciously organizes and deploys the skills at his disposal. Once triggered off by internal or external stimuli, the detailed components of a skill can be carried out without conscious control. Thus the skilled performer can direct his attention ahead of his actions. It is shown later that skill is likely to become more prominent when designing is aided by quickly responsive computers.

Procedures

Page, in his review of the papers presented at the Conference on Design Methods, noticed that in the enormous range of design procedures discussed, from regional planning to the design of scientific instruments, there was only one point of almost complete agreement. It is that designing is 'a three-stage process demanding analysis, synthesis and evaluation'. He thought that the cyclic nature of these stages should have been emphasized.

Mann suggests three major stages which he calls concept, analysis and specification. In beginning with a concept or solution, he differs from the theorists of systematic design but appears to reflect current practice in engineering and architecture. It may be that systematic design methods, being largely the means of formalizing what designers traditionally do in their heads, comprise an additional predesign sequence of analysis, synthesis and evaluation, the outcome of which takes the place of Mann's initial concept.

Asimow has suggested twenty-five stages for the engineering design process. Each stage is an iterative loop into which is fed the outcome of the last stage together with new information or an appropriate mode of analysis. Within each loop is a stage of synthesis followed by a stage of evaluation. In a case history of chemical plant design GREGORY (1964) describes fifteen major decision stages. In this example there were three feedback loops, the most troublesome of which involved the rather fruitless recycling over four stages.

Gregory notes that it is impossible to break out of such a loop without either feeding in new information or taking a decision that it is not fully supported by the information already available. The decision which he made was to choose a heater much smaller than any that had been found to work before, and which would operate near to the theoretical limit.

This decision, which was disputed at the time, but which apparently led to a successful new product, may be an example of the human ability to shift from one approach to another on the basis of inadequate information. Mann takes this to be the major difference between human and computer performance. Mackworth believes it to be the main feature of 'problem-finding', which he defines as the ability to detect the need for a new mental programme when the evidence is scanty. He points out that humans can do this repeatedly without starting afresh each time. He assumes that this is done by using previous experience as a code from which the missing part of the input is read when available information is fragmentary.

The Recognition of Structure

Inability to describe this coding procedure makes it difficult to programme computers to carry out recognition tasks without human aid. Mackworth suggests an investigation of the methods by which unfamiliar items are classified by the human brain. The points at which a classification is abandoned and a new one is started may correspond to O'Doherty's leaps of insight and Mann's creative peaks. On such occasions, the designer may be thought of as a circuit that is capable of damping small signals of mismatch between the structures of the classification scheme and the structure of the things classified (only some of which have yet been seen). He may also be said to be capable of resonance when there are signs of similarity between these two structures. The design process, with its orientation to what does not yet exist, involves not two but three structures that have to accord with one another. I find it useful to think of these as:

(1) The situation structure – The pattern of changing demands, competitive products and customer motivations from which the new design is expected to elicit a favourable response.

(2) The solution structure – The physical structure of a possible design.

(3) The resources structure – Relationships between the physical properties of the available materials, the limitations of available manufacturing processes and the costs of each.

The achievement of a good match between these three structures may be a criterion of good design. Any particular design procedure might be judged by its effectiveness, first in making these structures apparent, second in minimizing the structural mismatches of chosen solutions, and third in minimizing the total cost of the design process.

There are three further structures that seem relevant:

(4) The product life structure – The pattern of growth and decay of demand for a new product, the performance it achieves, its failures and its history of modification or further development.

(5) The designer's mental structure – The pattern of experience and ideas that is available to a designer when he examines a problem or considers a solution.

(6) The analogue structure – The patterns of external symbols or models which the designer uses to represent the structures of the situation, the solution or the resources.

Each of these last three structures is the major constituent of a method of designing. The most primitive of these, and also the most reliable, is the method of trial and error. A failure which occurs in the life of one product is corrected in the next without re-assessment of the design as a whole. The finest products of traditional craftsmanship were reached in this way without the intervention of any designers or other specialists. The developing of hand-built prototypes by trial and error is a modern version of this ancient technique.

The designer's mental structure plays the main part in the second method of designing –

that of simulating the product and exploring its properties in the imagination, aided by calculation, drawings and informed experience. This is of course many times faster than evolution by trial and error, and permits the re-assessment of the design as a whole. Provided the designer's experience of the design situation and of the resources is adequate, this method is very quick and reliable. It is the method by which most industrial products have been designed. Its weakness is its dependence upon past experience. As Page points out, experience is a double-edged weapon – it saves time and it saves thinking. The greater one's experience the more difficult it becomes to restructure one's thoughts to match the structure of new design situations, new solutions and new resources.

External analogues of the design situation, of possible solutions, or of the resources available, are dominant in the third method of designing. The aim here is to represent, outside the brain, the major part of the design process, so that it becomes visible as a whole (not piece-by-piece as it is in evolutionary trial and error). This externalized designing is no longer tied to the experience of one person. Greater leaps forward in design are possible because there is unlimited opportunity to restructure and test the relevant information patterns before finalizing the design. This systematic restructuring of thought enables a designer to explore more widely, and to test more precisely with reference to experience that is not necessarily his own. His skill has initially to be directed at the linguistic problem of creating a suitable problem-language which implicitly defines boundaries within which a host of alternative solutions lie. The design of flow systems is perhaps the only field in which externalized designing has been successfully applied to problems that are too large and too complicated to be formulated in any one brain.

Methods of Diverging

The common feature of the so-called systematic methods of designing (they are really methods of handling design information) is that they permit a widening of the area of search for interpretations of the problem and for solutions to it.

The essentials of each of the systematic methods to be discussed are *(i)* to break the problem into pieces, *(ii)* to solve each piece by itself, and *(iii)* to combine the pieces into a new whole which may surprise everyone including its designers.

This fragmentary treatment of a design problem is opposed to the development of overall concepts which Asimow and others take to be the basis of engineering design. However, if innovations in design are compared with what preceded them, it can be seen that this kind of breakdown and reconstitution is in fact achieved. In each of the innovations that is shown in *Table 32.1*, the novel solution is composed not of rearrangements of the existing parts, but of parts which are new in themselves. The divisions of reclassification of the problem into new functional components which these parts satisfy appears to be the creative step. The inventors concerned may not have set out to systematically reclassify existing functions but surely they were driven to take this step in moving forward from whatever were their conceptual starting-points.

It may well be that the second task of an inventor, that of eliciting sufficient response to his invention, is dependent on the rate at which his reclassification of functions can be appreciated by those who could use the invention. Only when his reclassification is understood, can the administrative reorganization that is necessary to exploit the invention take place. It is not until an invention has elicited this response, that it can be said to have become an innovation. Man–machine system design procedures include the formal consideration of this problem of assimilation of 'software' at the initial stage of design. It may be that in the increasingly organized world, the changing of software is becoming more difficult than the changing of machines. *Table 32.1* resembles the morphological chart that is described by NORRIS (1963). He shows how the use of charts can oblige a designer to think of several solutions for each of the major functional requirements, and how these solutions can be combined to form thousands and some-

Table 32.1

Existing whole	Existing parts	Existing classification of functions	New classification of functions	New parts	New whole
Cut-throat razor	Blade	Cutting	Cutting edge	Thin blade	Safety razor
	Handle	Control	Stiffness of edge	Blade clamp	
	Strop	Sharpening	Control of angle	Edges of clamp	
			Control of strokes	Handle	
			Maintenance of edge	New blade	
Retail shop	Counter	Buying and selling	Selection of goods	Self-service displays	Supermarket
	Shelves	Availability of goods	Payment for goods	Checkout area	
			Replacement of goods	Service staff	
Aero engine and propellor	Engine	Power	Admit air	Inlet	Jet engine
	Propellor	Thrust	Accelerate air	Compressor	
	Fuel	Power to engine	Expand air	Burners	
			Expel air	Outlet	
			Power to accelerate air	Turbine in expanded air	
			Power to expand air	Fuel	

times millions of alternative designs. A less formal method of achieving a wide range of ideas is the 'brainstorming' meeting proposed by OSBORN (1963) and by other advocates of creativity in design. Persons of varied experience are asked to suggest any conceivable way of tackling a design problem. The inhibiting effect of criticism is avoided by a rule that no idea is to be evaluated until the meeting is over. TAYLOR, BERRY and BLOCK (1958) have shown that group 'brainstorming' does not produce better ideas than does solitary thought. There is, however, little doubt that it is an extremely quick way of extracting information from the memories of persons whose experience is relevant to the problem. For some time at Manchester, an elaboration of brainstorming had been used for collecting quantities of design information (JONES, 1964). Each person concerned is asked to read journals, examine existing products, talk to users, and speculate privately. He writes each relevant thought or fact he comes across on an index card. The cards are read out in random order at a meeting and many more suggestions are then made, each of which is written on a card. The structure of the problem is examined by classifying and reclassifying the cards in different ways until a structure that seems realistic to the designer emerges.

Page describes these techniques of

divergence as 'planned relearning in a framework that forces divergent rather than convergent thought'. The difficulty here is to pick out usable ideas or approaches from the mass of material which is generated. Unfortunately, neither brainstorming nor morphological charting includes a reliable way of doing this. Experience of card sorting suggests that one may nevertheless benefit from the restructuring of one's thoughts.

JONES (1963) and Matchett both describe more controlled methods of widening the area search. Matchett suggests beginning from a definite starting point, such as a tangible weakness of an existing design, and then permuting possible causes and remedies in a formal way to expose the whole problem. My method is to write performance specifications for each of a number of critical requirements and to combine partial solutions into compatible sets. A difficulty with these methods is that conflicts arise between the structure of the analysis and the structure of one's thoughts. MATCHETT (1964) advocates the use of social pressure to induce a designer to abandon his old thinking process and to stick to his analysis. I favour the abandoning of an analysis in which one has lost confidence, and the starting of another which is closer to one's present view of the problem. This difficulty of reconciling formal methods of exploration with the freedom to change one's mind, in response to signals of mismatch between analogue structure and mental structure, is something to which more attention could be given.

Methods of Converging

At this stage in designing (which for Asimow, Mann, Moulton and others appears to come very soon after the start) evaluative rather than exploratory techniques are needed. PAGE (1964) discusses the strategy of beginning with models of alternative solutions that are as rough as can be tolerated, and testing them in an analogue of the design situation. This intentional roughness avoids spending design effort on detailed studies of designs that may later be found to have major faults. A diverging idea must not be developed very far unless there is evidence of convergence on an optimal solution. MARPLES (1960) has shown how engineers direct their knowledge and experience to the avoidance of blind-alley design decisions which are likely to create difficulties at later stages.

In suggesting a fairly formal path of convergence on one solution Matchett (1963) and Asimow both state that goals must be very clearly stated and fixed at the start. Asimow's major stages in this convergence are:

(1) Feasibility – A set of feasible concepts or outline solutions.

(2) Preliminary design – Selection and development of the best concept.

(3) Detailed design – Engineering description of the concept.

(4) Planning – Evaluating and altering the concept to suit the requirements of production, distribution, consumption and product retirement.

ROSENSTEIN (1960) put forward a system design procedure which is similar:

Identification of need.
Information collection.
Identification and statement of system variables:
  inputs
  outputs
  transforming means
  constraints.
Criteria for optimum design.
Synthesis for:
  physical realizability
  economic worthwhileness
  financial feasibility.
Optimizing and sufficing.
Test and evaluation.
Iteration.
Communication, implementation and presentation.

The difference between these descriptions of engineering design convergence and some of the more divergent systematic techniques is that, in the latter, solutions to parts of the problem are evaluated and converged upon before the general form of the design has emerged. In the former, a concept for the whole design is chosen before detailed evaluation takes place.

Strategies

Asímow suggests that the choice of techniques for tackling any problem is a unique tactic. It is likely that any of several such tactics would reach an acceptable solution provided there are plenty of iterations in each. The route chosen may be influenced by the designer's temperament and preferences, but the solution reached must be workable and must be shown to be so. Simon and Simon, in their computer simulations of chess playing, have shown how the best players have successful strategies which lead from one to another without exploration of more than a fraction of the alternatives and without needing to think further ahead than the location and identity of the next strategy. Such behaviour seems alien to the following through of a pre-established series of stages in design, but not to the seemingly impetuous changing of techniques as the work proceeds.

Two strategical points can be mentioned. The first is 'minimum commitment'. This is Asimow's term for the principle of taking only those decisions which are necessary to the stage that has been reached in the design process. Other decisions should be deferred so as to leave maximum room for manoeuvre at later stages. This principle is difficult to stick to if there are feedback loops over several stages arising from interactions between detailed and general aspects of the product, a difficulty that is particularly noticeable in architectural design.

The second strategical point is the choice between in-out and out-in design sequences. The design of a house can begin with an exterior into which is fitted a plan and then rooms into which is fitted equipment. Alternatively the designer can begin with activities and equipment and move outwards to rooms, to a plan and lastly to exteriors. In practice he may use both sequences in turn. This is the familiar conflict between starting with overall concepts or starting with solutions to parts of the problem. The out-in sequence is likely to be quicker, and the in-out sequence is likely to be more reliable. I have not come across evidence that it is essential to use a combination of both sequences, or that there are design situations in which one or other of the sequences, in its pure form, has a clear advantage.

Computer-aided Designing

Questions of design procedure which are of academic interest when design thinking occurs in one person's brain, become of practical importance if that thinking is to be shared with a digital computer. As Mackworth (1964) and Mann point out, it will one day be possible to provide designers with individual and speedy access to computers via keyboards and quickly-responding displays of the 'sketchpad' type (SUTHERLAND, 1963). The major weakness of present computers, that of being unable to change programmes quickly (Page, 1963) will thereby be removed. As Mackworth (1964) has remarked, 'no other devices in the world are quite so badly designed from the point of view of ease of human use'. Mann envisages programmes which are not fixed in advance but which are capable of, and require, human intervention at crucial points. He suggests that the languages used should be graphical and verbal, as well as mathematical, and that they should permit the designer to explore complex situations that he himself does not fully understand. The time of response should be equal to, or less than, the designer's 'cognition delay time', so that he can 'mold, shape, interrupt and redirect the computer's manipulations' in response to his evaluations and judgments of a developing situations. This is the antithesis of the present use of computers for the completely automatic exploration of those sections of design problems which are well understood.

BOSTON (1963) has successfully used a computer programme which is dependent on the responses of an experienced designer. His experiments suggest that the effect of the computer aid is to permit the designer—computer combination to make better-informed leaps to a new design possibility, when the designer decides to reject the last design possibility which has been printed out. This is because the machine can take account of details of the designer's previous judgments which he himself cannot recall in detail. The effect of the designer's interventions is to direct the process of automatic exploration away from unfruitful searches which might otherwise overtax its storage capacity. It is thus possible to jointly undertake problems of a very large mathematical scale.

Mann picks out speed, memory and reliability as the predominant characteristics of a computer, and suggests that it be applied to the mechanization of all design experience that the designer himself understands. What he does not understand, but is nevertheless capable of dealing with, is left to the human intelligence. Anything that becomes understood in the course of joint exploration is thereafter the responsibility of the machine. Mann's creative peaks are thus crowded together because the machine takes over most of the 'grunge'. I imagine that this change would greatly accelerate innovation, and raise the intensity of a designer's work to something like that of a tightrope walker or a concert pianist.

Mann also suggests that computers should be used to store details of standard parts, the properties of materials, standard procedures, and the history of previous designs, successful and unsuccessful. The designer should be presented with the possible alternatives from this store of information 'upon making an absolute minimum query to the computer'. At intermediate stages the computer should be able to check the geometrical compatibility of parts, and to plot the repercussions of changing a particular detail. When a satisfactory design has been reached, the computer 'should generate drawings, parts lists, numbers of fasteners, *etc.*, as well as prepare the director tapes for the numerically controlled machine-tools which will produce the product'. Mann does not consider the possibility that computer-aided designing would release the designer from his present need to think in terms of solutions to the problem as a whole. The prior exploration of solutions to parts of the problem, which is a feature of systematic design as we now know it, might be a more suitable basis for computer-aided designing.

Computers have already been used to generate manufacturing information for new products that can be made up of existing component types according to standard rules. The critical problem of capturing the design logic of the engineering designers who formerly did this work, has been solved by the use of decision tables for recording each item of design procedure (IBM, 1962).

Organization of Designing

Page (1963) suggests that the organizers of creative work have two main functions: First to provide talented persons with the best available tools, and second to provide a framework within which they can work with a feeling of security rather than insecurity. Mackworth (1964) notes the outstanding fact that the social and intellectual environment is of much greater importance to original work than is the physical environment.

I have previously suggested (Jones, 1963) that a new kind of design organization may be necessary to permit a complete change to systematic work. The elaboration of the preliminary stages of design is likely to require the setting up of specialist predesign sections, which are insulated from day-to-day contingencies and which operate on longer budgeting periods than are normal in design and development. The cost and time of this extra work early in designing would be justified only if the total development costs are lessened, and if the tendency to over-run delivery dates is thereby kept under better control.

Mackworth (1964) concludes that a single brain is better than a group of brains for deciding, at the start, the general character of an investigation. He also notes that co-operation from persons of diverse experience is of more value before and during the development of an idea than in subsequent assessment of its worth. Environments which encourage accidental meetings of reasonable duration and frequency are valued in this respect.

The assignment of problems to interdisciplinary or interprofessional groups seems to be essential if really novel problems are to be tackled successfully. Some of the difficulties of doing this have been described by

LEWIS (1963) in his precise and involved description of the reasons why group members are either unaware of the misunderstandings that are almost certain to arise between them, or are unable to progress on a broad front once they realize what is going on. He suggests that means must be found to give each member an influence commensurate with his knowledge of each of the topics that are discussed. Page (1963) has referred to the example of the building industry in which the different professional groups attempt to pursue incompatible strategies set by their different frames of reference. When effective interprofessional groups are established, there remains the problem that the persons concerned feel cut off from their chances of promotion if they stay too long away from their own fields.

Despite these and other difficulties, some ways of enabling mixed professional groups to deal with design situations will have to be found. Otherwise society will be overwhelmed by large-scale problems such as traffic congestion, road accidents, crime detection, food shortage and housing shortage, each of which seems incapable of solution by the unaided efforts of the professions that are traditionally concerned.

Chapter 33

TECHNOLOGIES AND VARIETIES OF DESIGN

W. E. Eder

Introduction

Chapter 3 of this book has outlined the general design process in an industrial environment. This process seems to be generally applicable to most technologies, and even finds some parallels in the design of research apparatus and experiments. Mostly, the pressure of the environment forces the engineering designer to work in the way that has been seen to give quick results, and allows him little time to experiment with other methodologies. The methodologies outlined in Chapter 3 were:

(1) Experience – developed by the individual in his own way, during his working life, to deliver new solutions.

(2) Modification – redesign after experience to take new circumstances into account.

(3) Check-lists – an attempt to list all possible influences, in order to channel and free the designer's mind.

(4) Design tree – a method of recording the steps in a decision process, in such a way that the designer can review his progress and recall the reasons behind his decisions.

(5) Fully systematic methods – a form of data processing to free the designer's mind still further, and allow him to tackle more complex problems with better records of previous work.

(6) System search methods – useful when a system must be found, and the components or elements are already in existence or can be made with existing technology.

In methodologies *(3)* to *(6)*, the purpose is to allow the designer to follow two or more possible solutions for an appreciable length of time. The designer should avoid 'falling in love' with any one solution, delaying a decision on which solutions to drop until the decision can be made on objective criteria, or at least until the criteria are very much clearer than at the outset.

This state of mind, although difficult to attain, should yield the best possible solution in the time available. More time can be concentrated on the earlier stages, and a better basis created for the final design of the preferred solution. The obvious disadvantage is that the 'boss' does not see enough on paper in the early stages, especially very few drawings.

It does not seem necessary to work through a problem whilst adhering rigidly to any of these methodologies. Good designers use routines when they consider them helpful, and drop back on experience when this can lead to a quicker result. Some of the existing technologies are now discussed in this light.

Technologies

Mechanical Engineering

I propose to start with the technology with which I am most familiar, and to which many other technologies turn for at least a part of their ultimate hardware – mechanical engineering. Most of the innovations in this field have been attributed to lone designers of no little genius using methodology *(1)* listed above. Many names spring to mind immediately – Watt, Stephenson, Brunel, Kaplan, da Vinci, Issigonis, Whittle, *etc.* Their work has been continued and improved by nameless hosts who have relied mainly on methodologies *(1)* and

(2), although in some cases methodologies *(3)* and *(4)* have also been used. The salient feature of most artefacts produced in this way is that they have been regarded as separate 'machines' with a specific job to do, but largely independent of the more subtle inputs, and with little regard to the eventual output; the drawing is extremely important both during the thinking (incubation) stages, and for communication (see also CLAUSEN, 1958). Only very recently has this fraternity (among which I count myself) started to realize that a diesel engine, for example, is a system with a feedback loop (through the governor to the fuel pump), and it can therefore be investigated for dynamic response by using mathematical models; also, that a machine-tool is a part of a production system, connected by a transport system with other machine-tools, and therefore queueing theory and operational research methods are applicable to it – which implies using statistics.

Mechanical engineering designers are frequently concerned with mechanisms and their components. The optimum synthesis of mechanisms has also received much attention recently, resulting in works by BEYER (1965), TAO (1964), FREUDENSTEIN and SANDOR (1961) and others. This requires an investigation of the need for a mechanism (*e.g.* the bucket movement of an overhead loader) and the motion it should perform, and this synthesis can then give the principal (functional) dimension of the components needed to produce the motion. The positions, velocities, accelerations and forces in each component must be determined. Their material dimensions must be calculated to prevent static failure under maximum load, with checks on other failure modes such as elastic buckling (overall in bending or shear, and local), creep, and fatigue (in stress-concentrating steps and fillets, or due to rolling or sliding contact). This latter procedure must take due account of the materials, method of production, *etc.*, to yield a working specification (drawing) of the component. The parallels to the general design process of Chapter 3 are, I think, reasonably obvious; the sponsor (the system designer) and the customer (the workshop) are here in the same production organization. Check-lists and checking personnel can reduce the number of errors introduced in detail design, and should be used frequently. See, for further detail, Chapter 22.

The position in jig and tool work is very similar and depends to a large extent on craftsmanship and its thorough appreciation. Therefore methodologies *(1)* and *(2)* are the most frequently used, although much of the work is done with standards and recommendations (check-lists in an extended sense) in constant use. This situation is not likely to change much in the foreseeable future, except where automation rears its head.

In the machine-tool field, much traditional work is still done – methodologies *(1)*, *(2)* and *(3)*. This is being augmented by the automatic control of machine-tools, by both interchangeable cams, as in the repetition automatic lathes, and by numerical control programmes (position and continuous path) which require considerations of the response of the machine-tool and its control apparatus. This is the system engineering approach *(6)*. Numerical control is tending to make the detail (component) drawing obsolete, since a punched or magnetic instruction tape is needed and the 'draughtsman' or detail designer must learn this new 'language of communication'. Some notes on trends appear in the informal discussion published by the institution of Mechanical Engineers (1965).

Powered Manual Equipmont

Hand-tools, although basically mechanical engineering artefacts, usually with strong electrical connections, have some extra problems of aesthetics and ergonomics superimposed. The shape of an electric hand-drill is determined partly by the electrical and mechanical interior. But it is especially determined by the need to apply pressure by hand in a well-specified direction with reasonable comfort, to avoid muscle fatigue and cramp, in the usual conditions (oily hands?). The drill must also appear pleasing.

Domestic appliances are dominated even more by aesthetics, which must be included in the design process in a prominent position during problem-solving, together with the consideration of noise. The market is very 'looks' conscious. In both these cases the usual approach is via methodologies *(1)* to *(4)*, although *(6)* is sometimes required where the 'automatics' are not merely set-time switched, but controlled by some process variables.

Electronics

Electronics has been one of the traditional hot-beds of the systems approach, using standard components like valves, transistors, resistors, capacitors, *etc.* Methodology *(6)* is almost universally used for design of equipment; the components are more frequently developed from results of pure research by trial and error technology on the shop floor – methodology *(1)* or *(2)*. This industry is discussed in more detail in Chapter 34.

Data transmission has some peculiar problems of its own, especially as it is concerned in one of its methods with microwave electronics, guided in cavities that are surrounded by mechanical engineering problems of materials, accuracies and production methods. Therefore all the methodologies find some use.

Heavy Electrical Engineering

Design work in electric power is distributed between at least three different branches. One branch is concerned with the distribution of electric power, and therefore uses the system concept with all its analytical forms, as indicated by MORTLOCK (1964). Design is restricted, according as to whether the need for expansion is progressive, and whether additions to an existing system to increase the magnitude of input and output can be covered by basically analytical techniques. Power generation technology provides the means of adding to the input. It is concerned with systems for control, with mechanical and civil engineering (the separate machine idea) for the generators and prime mover equipment and with the design needs outlined by TURNER (1964). The way in which the output is absorbed, does not yet show much consciousness of the systems idea, in particular regarding the 'upstream perturbation' effects of connected equipment. However, these considerations are being forced by the application of tariffs – although the results may only be a 'hit and miss' approach to power factor corrections.

Hydraulic Engineering

Hydraulic engineers are in a much more favourable condition since they must consider the system. Hydropower works on the environmental system of rainfall collection and drainage. In spite of this, methodologies *(1)* and *(2)* play the largest roles in design work, coupled with model tests in an attempt to eliminate the imponderables. Hydraulic transmission work is very system-conscious and the use of methodology *(6)* is frequent, even though the number of available elements is probably larger than that of the electronic engineers (mainly because a frequent transfer of electrical/mechanical-to-hydraulic and hydraulic-to-mechanical/electrical functions is required to design an effective and useful system).

Chemical Engineering

Chemical engineering also has some peculiar problems, in particular regarding the chemical behaviour of matter (reaction dynamics) and the artefacts needed to contain the media. This technology has a great interest in continuous working. Methodology *(6)* should be found very useful to determine the possible strings of reactions, separations, heating and cooling, distillation, *etc.* (termed 'unit operations' and 'unit processes'). It should also be useful in attempting transformations into hardware units (distillation columns, heat exchangers, reactor vessels, filters, *etc.*) in the most economical way. At present, methodologies *(2)*, *(3)* and *(4)* tend to be used. Once the chemical process and the flow design (determining the space required for the reaction) have been achieved, the mechanical design of the separate hardware units can proceed methodologies *(1)* to *(4)*. Their layout can be determined using all available tricks, including models and analytical calculations with due regard to cost, heat losses, *etc.* This wider and conscious picture of chemical engineering design is still rare within the technology. Much of the hardware design concerns pressure vessels and involves interpretation of the relevant codes.

Complex Problems

Methodology *(5)*, hardly mentioned so far, has been developed to cope with far more complicated problems, such as occur in municipal engineering, many architectural and planning situations, transport system design, and nuclear power generation. The problems are aggravated by the large number of variables, and the scarcity of definite information. As this methodology becomes more universally known and accepted, its range of use will probably be extended. It requires conscious, deliberate and careful application and the first few times will probably prove a disappointment–'I could have done it easier by guesswork'; but I feel it is worth persevering, especially as Britain's position in the world today depends not only on innovation and research, but even more on the application of these in profitable industries.

Components

Once the system or the basic function of the mechanism has been decided, it must be broken down into the elements and components from which it is to be assembled. Elements and components are frequently of a mechanical nature, although a parallel may be found in purely electrical components, and therefore intend to show that the sequence of design for a mechanical component fits reasonably into the pattern described in Chapter 3.

The sponsor is invariably the designer who decided on the overall scheme of function. His requirements are stated in terms of power, speed, flow rate, pressure, force, *etc.*, and the variation with time. In order that the system shall not fail, the component must be designed in such a way that it will not fail either in function or in structural integrity. Therefore the analysis of the sponsor's requirements must be based on the modes of failure.

As the sponsor is concerned mainly to prevent functional failure, this must be the subject of the feasibility study. The laws of mechanics, *etc.*, must be applied to the outline mechanism suggested by the sponsor, and certain minimum (and/or maximum) dimensions determined. Limiting conditions will be set by frictional slip (where forces must be transmitted from one contacting face to another), contact stresses, bearing loads and load carrying capacity, lubrication, wear, life, or similar considerations for a mechanism; a structure is limited by deflection, rigidity, collapse loads, *etc.* Certain assumptions must already be made to solve the equations. Evaluation criteria derived from this study are set in terms of the sponsor's requirements, cost, overall size, and possibly aesthetic, ergonomic and other considerations. The sponsor should again approve the work up to this point.

The problem-solving step is concerned with preventing failure of structural integrity in the component. The effects of load, the actual (and assumed) distribution of stress in the component, and the failure modes of yielding, fracture, fatigue, creep, structural instability (buckling), *etc.*, must be dealt with; also the effects of surface finish, stress concentration, corrosion, *etc.* All of these are amenable to calculation in an analytical sense, but design (the determination of the necessary dimensions and geometry) demands an inverse approach which is not always possible. Problem-solving is therefore again a cyclic process which takes all possible failure modes and inaccuracies of available data into account.

Only two failure modes mentioned above show a direct relationship between load and the properties of a cross-section: yielding, and buckling of a perfect column. In each case the stress is assumed to be evenly distributed throughout the section, which is sufficiently close to reality for ductile materials. Minimum sizes may therefore be obtained for the cross-section to carry the maximum load (tension, compression, torsion, bending) without failure by overall yielding or buckling. If necessary simplified assumptions, with increased safety factors may be used, followed by checking with the full load. The other failure modes depend in some way on the shape of the component and the local geography. It is therefore important to decide what steps, enlargements, fixtures, *etc.* are required for the component to function properly. The component must then be checked to establish whether the other modes of failure can occur with the proposed geometry, and whether the geometry can be modified to prevent this failure mode (by reducing the elastic stress concentration, improving surface finish, possibly by increasing the basic dimension, or altering the force application). Examples of this type of approach may be found in EDER and GOSLING (1965), and in a paper by EDER (1964). If this approach is used, the safety factors need only cover inaccuracies in data. An attempt to cover other failure modes must fail due to their dependence on local geometry.

In the real engineering situation the sequence of events is usually not so straightforward. The shape and size of any one component can and does react on other components in the same assembly. The problem then exhibits an extra cyclic loop, feeding back from the failure considerations of the individual components to the overall function. In effect, the dimensions of the assembly and its components must be optimized to produce an economic compromise solution. This requires some skilful juggling with sizes of each component and their effects on the other components, or between the sizes of different parts of a component, sometimes even between operational principles. Once more, the advantages can be seen of dealing with more than one solution until a clear and objective ranking of the solutions can be obtained.

The general design methodology covering this sequence is the check-list methodology *(3)*, with some use of the design tree *(4)*. It contains a large number of calculations, some of doubtful accuracy, and requires wide experience to cut this work down to a minimum. Calculations should be made wherever reasonable doubt about structural integrity exists: 'running redesign' on the development test-bed is no substitute for careful work in detail design.

Acknowledgments

I wish to express my sincere thanks to Mr. S.A. Gregory and Mr. W. Gosling for their help in preparing this Chapter and Chapter 3, and the University College of Swansea for the opportunity to indulge in work of this nature. The opinions expressed, in particular regarding the uses and usefulness of techniques and methodologies, are my own, and I take full responsibility for them.

Chapter 34

PRELIMINARY RESEARCH INTO ELECTRONICS DESIGN

H. V. Beck

Introduction

An *ad hoc* Committee on Electronics Design has been set up within the Electronics Division of the Institution of Electrical Engineers to study the basic design processes and organizational procedures used in the electronics field, and to determine if any gaps exist in the information available to the electronics designer. The work of the committee in preparing to carry out its mandate may be of interest to corresponding bodies in other fields and is outlined here.

Ad Hoc Committee on Electronics Design

Most members of the committee were invited to serve because of their interest in the manner in which design is carried out. All are professional engineers and most are electrical engineers, at least four of whom have had extensive experience of design in the electronics field. Specialist experience of members of the committee covers such topics as aesthetics, sociology, management and teaching. One member is the nominated representative of the Electronic Engineering Association and another of the Naval Training Department of the Ministry of Defence.

Published Material

One of the principal problems facing the committee was the lack of published work about the manner in which design is carried out in the electronics field. There are numerous papers covering the design of devices, circuits and systems, but almost without exception these concentrate on the purely technical aspects and on the end-result of a design exercise, rather than on how the particular configuration has been evolved. The philosophy of design can now be seen emerging as a discipline, but up to two or three years ago most work on these lines was of a speculative nature (BECK, 1961). No formal papers had been published on design processes in the electronics field, and the few pioneering design philosophy papers in other engineering disciplines (MARPLES, 1961) tended to concentrate on design problems in which there was a well-specified objective and on the purely logical aspects of design, both of which relate to only a small part of the electronics design field. The flexibility of electronic techniques makes electronics design problems particularly open-ended and, because of the complex behaviour of electronic circuits and systems, logical design forms only a part of the electronics designer's activities.

Conference on Electronics Design

In view of the lack of published material, various concepts and proposals were evolved *a priori* by members of the committee before it held its first meeting in September 1964, and it was decided to hold a conference in February 1965 to obtain reaction to these ideas. The conference itself was something of an open-ended design problem. The committee was acting as an inexperienced design team for unspecified customers' unknown needs, using slender and unfamiliar resources. In a manner appropriate to the electronics field, it was decided to organize the conference on a 'breadboard' basis.

Speakers were sought and invited to cover such topics as characteristics of the equipment; the emphasis given to particular characteristics in various fields of application; studies of problem-solving activities; various aspects of industrial design; information required by the electronics designer; and the teaching of electronics design.

In arranging the conference, the topic of circuit design was deliberately avoided although it did in the event appear in the teaching session. Considerable interest in the conference was expressed by staff of universities and colleges of technology concerned with introducing more design work into their electrical engineering courses, and by administrators, design managers and chief engineers professionally concerned about the efficiency of design. It was important that the views of designers themselves should be expressed at the conference, and a special effort was made to arouse their interest. An article by BECK (1964) was published in the *Journal of the Institution of Electrical Engineers* giving the background to the conference.

The conference proved very satisfactory. Some 300 engineers, including designers, teachers and managers attended the conference and there was a useful exchange of views.

Electronics Design

Enquiries into design processes and practice are now being carried out in several engineering disciplines. Useful concepts and results of possible general validity are being promulgated and one approach to the study of electronics design would be to examine these results and seek to apply them to the electronics design field. There was a considerable incentive to do this in the Institution of Electrical Engineers, which covers both the purely electrical and electronic fields, with examples of design ranging from power stations to transistor radios. Concepts of engineering design covering all fields are, however, likely to be too general to apply to particular disciplines. For example, words have quite different meanings and significance in different engineering disciplines; the word 'drawing' means much more to a mechanical designer who works most of his ideas out on a drawing board, than to an electronics designer whose mode of expression is via the circuit diagram and for whom drawing is a rather routine operation. Until there is a common language or convenient notation for relating each facet of design in a given field to a common set of concepts, it is difficult to see how an applicable generalized notion of design can arise. It was therefore decided to concentrate on studying electronics design in depth, taking as much account as possible of work in other fields. Concepts and models can be compared later with those of other fields and appropriate adjustments made to fit more general models of design. Specializing in electronics design can also be justified by the greater ease with which the knowledge generated may be applied to the training of engineers to design electronic equipment.

Hierarchical Considerations

The electronics design field is itself large enough to make a choice of area within the field necessary for initial study. There is a hierarchy of complexity extending from supersystems (as required for global satellite communications) down to the parts and materials from which devices (such as transistors) and components (such as resistors, capacitors or inductors) are manufactured. *Table 34.1* gives some examples at various levels in the hierarchy of complexity.

By examining, in a general way, the attention given to various characteristics at different levels in the hierarchy, one comes to the conclusion that the greatest diversity of characteristics occurs at about the equipment level, (see *Figure 34.1*). Size, weight and appearance, for example, are characteristics of a television receiver but not of a television network. The electronic expertise required for design at the supersystem level is practically none, and increases towards the systems and equipment levels and reduces again at the devices and components level where the knowledge required is predominantly of physics. Considerations such as these have led to the confinement of the field of study to the equipment level.

Specialized Aspects

Electronic techniques have made an impact in most branches of human activity; the use of the proton resonance detector in

Table 34.1

Supersystems	**National defence radar networks; Eurovision**
Systems	**Ship's radar; a television network**
Equipments	**Radio and television receivers; oscilloscöpes**
Functional modules	**Decade scalers; analogue/digital converters**
Circuits	**Binaries; cathode followers**
Devices and components	**Transistors, triodes, resistors, capacitors**
Parts and materials	**Silicon chips; ceramic tubes**

archaeology, computers in business, and electrocardiographs in medical diagnosis, are indications of their extreme flexibility. The flexibility is to a large extent due to the wide range of functions that may be obtained by minor changes in circuit configuration or values of components, and this gives rise to certain unusual problems in electronics design. Considerable attention to fine detail is required to ensure that the necessary function is obtained under all normal conditions of manufacture and operation. This detail includes unseen 'components' such as stray capacitance which could have a marked influence on performance.

Thus, the designer of electronic equipment has to make a very large number of small-value decisions. A typical electronic equipment might contain 1,000 components and devices, and associated with each are several decisions relating to circuit function, cost, quality, reliability, safety, and so on. In a circuit, for

	Characteristics											
	Cost	Versatility	Reliability	Performance	Novelty	Ease of use	Maintainability	Developability	Adaptability	Appearance	Size	Weight
Supersystems	+	+	+	+	+		+	+	+			
Systems	+	+	+	+	+	+	+	+	+			
Equipments	+	+	+	+	+	+	+	+	+	+	+	+
Modules	+	+	+	+	+		+	+		+	+	
Circuits	+	+	+	+	+		+	+			+	
Devices and components	+	+	+	+	+			+			+	
Piece parts and materials	+	+	+	+	+						+	

Figure 34.1. Characteristics at different hierarchy levels

example, a resistor costing a few pence has to be defined in terms of electrical value, tolerance, power, type of construction, position and wiring arrangement to take account of amplification, frequency response, d.c. conditions, breakdown conditions, supply voltages and temperature changes.

Another particular feature of electronics design is the wide range of effects and parameters which the designer may encounter. Frequency ranges from 10^{15} to 1 are possible, taking the limits of present-day achievements. Frequency ranges from 10^6 or 10^7 to 1 are quite common in a single equipment – a television receiver, for example, incorporates 50 c/s techniques in supply and frame generator circuits, and 50 Mc/s in the receiver. Voltages are quite commonly in the range from 10^7 to 1, as is indicated by overall amplification of this order.

The next point is that in the electronics field there is probably more design of complex general-purpose equipment or equipment with open-ended specifications, than in other fields. A general-purpose oscilloscope has its counterpart in a lathe, but the choices available to the designer of an oscilloscope are very much wider than those for a lathe.

Finally, the rate of change of techniques, devices and components is probably greater in the electronics field than in most others. It is unlikely, for example, that such a radical change has taken place as that due to the introduction of the transistor. Other technological developments, such as the monolithic construction of circuits, are likely to have as significant an effect.

For these reasons also it is desirable to study design processes for electronic equipment in particular, leaving comparison with other fields to be made at a later stage.

Definitions

There are many different interpretations put on the word 'design' To some it signifies 'appearance', to others it is that part of the evolutionary process of an equipment that takes place in a drawing office. Many regard it as an activity which is by nature purposeful rather than accidental. Everybody, according to his own experience or organization, has his own view of design. Attempts have been made to define 'design' rigorously to take account of one or more of these points of view. ROSS (1964) puts forward the definition:

> 'Design is the process of conceiving, refining and recording plans, which if carried out would lead to a high probability of effective accomplishment of an interrelated set of desired goals without the occurrence of penalties such as would be regarded by informed contemporary opinion in the context as unnecessarily, or substantially, offsetting the desirability.'

Another approach is to formulate a definition which embodies those aspects of design which need particular stress at any given moment. KANTOROWITZ (1958) points out that for at least two thousand years attempts have been made to define 'law' rigorously, with rather unsatisfactory results. It is preferable to adopt a conceptual pragmatic approach, *i.e.* a definition based on 'what should be' rather than 'what is', and which is fruitful for the purpose of the particular exercise.

The definition of the design of electronic equipment, called a working definition, adopted by the committee was: 'Design is the process of establishing relationships between all relevant characteristics of an equipment.'

Some of the characteristics by which equipments can be described are given in *Figure 34.1.* At the equipment level of the hierarchy, design consists of finding a set of relationships between the characteristics; just as at the circuit level, design consists of establishing relationships between, say, amplification, bandwidth, output voltage, reliability and cost. In establishing relationships, account must be taken of the use to which the equipment is to be put and of the objectives, facilities, and restraints of the organization in which, or for which, the design is undertaken – this is an essential condition for successful design.

Conceptual Models

In order to study the practice of design in the electronic equipment field, a picture of the design activity as a whole is needed so that the relationships between the various aspects can be seen and understood. However, design is such a complex operation that the picture needs to be a composite one, built up from a series of models reflecting different points of view. Thus, for example, one model may be evolved on the basis of information flow, another on materials processing, and another on human relationships.

In dividing up the whole design field into various study areas it is neither necessary nor desirable to follow the existing conventions or demarcations. As with definitions, the models may be based on a conceptual pragmatic approach, *i.e.* established on a higher level of abstraction than present practice and in groupings and terms which may be readily understood and easily applied by those directly concerned. The models should at first be extremely simple so that fundamental areas of enquiry may be indicated.

The Design Nucleus Concept

The individual designer is a rarity, at least on the equipment level. Design more often takes place by teams, but even this is something of a limited picture when consideration is given to the manner in which a given set of relationships is established between the characteristics.

A user stating the requirements for each characteristic, taking into account what can be achieved, has carried out the basic design of the equipment. A circuit engineer, salesman, production engineer and user corporately drawing up an achievable specification of all the characteristics have taken a major step in designing the equipment. A product policy committee deciding on the emphasis to be given to the various characteristics are exercising a design function. There is in any organization a section or committee or informal association of people which plays a leading part in determining the set of relationships of characteristics. This may be called a design nucleus rather than design department or team. The design nucleus may vary from product to product according to the knowledge, experience, status and motivation of persons within and outside the organization. The design nucleus concept is important when considering the manner in which the set of relationships is established.

Materials-handling Model

Design can be regarded as a major part of a process which results in instructions or information for the conversion of materials to equipment. Materials come into an organization which manufactures electronic equipment as components, devices, sheet metal, *etc.* The same materials come out of the organization modified, adorned and combined in the form of electronic equipment. The simple model shown in *Figure 34.2(b)* identifies three areas:

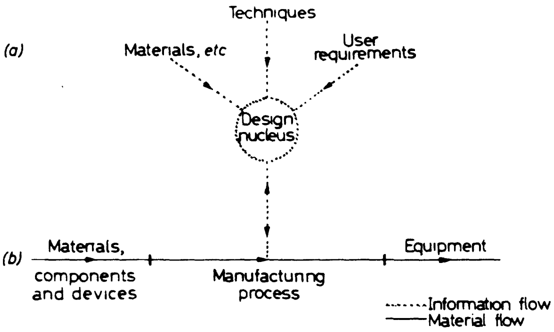


Figure 34.2. (a) Information required by design nucleus; (b) handling of materials

Characteristics of the Equipment – The characteristics need to be identified and defined. The units in which they may be measured and their relationships should be examined.

Materials, Components and Devices – In addition to normal constructional and finishing materials (*e.g.* plating), electronic equipment requires components such as resistors, capacitors and inductors, together with devices such as diodes, transistors and cathode ray tubes in considerable variety and quantity. A list needs to be made of these items and their characteristics, related to the type of electronic equipment produced. The effect of availability and standardization on design should also be determined.

Manufacturing Processes for Electronic Equipment – Manufacturing processes particularly applicable to the electronic equipment field have been devised or adopted, and these have a marked effect on design. Conducting protective finishes, dip soldering, printed wiring, simultaneous wiring and testing, and thin film and integrated circuit construction are among many aspects of manufacture that have to be taken into account. These processes should be listed and described.

Model. Based on the Information Required by the Design Nucleus

If design can be regarded as a major part of a process resulting in information which enables materials, components and devices to be converted to equipment, what is the information required at the input? The model shown in *Figure 34.2(a)* indicates four areas:

Materials, Component and Device Information.

Techniques Information.

Characteristics Required by the User – Users can be divided into various categories, for instance the single user, the multiple user with identical purposes, and the multiple user with varied purposes. How can information be collected from the various classes of user? What are the market requirements? What set of emphases is given to the various characteristics in a given field of application.

Manufacturing Processes – See above.

The Design Process

In the design process, the information received by the design nucleus is used and supplemented by, for example, an idea or by deduction. What does the designer do with the incoming information? Topics that should be covered are:

Identification of the starting point of the design process.

Judgment, decision, decision trees, iteration.

Synthesis, optimization, reconciliation processes.

Random, creative and logical elements.

Thought processes particularly relevant to design.

Psychology of designer.

Creativity in design.

Communications Between the Design Nucleus and the Design Organization

Communication between the design nucleus and the organization takes place in a variety of ways and for many purposes. Forms of communication are the instruction to proceed with the design, the design appraisal meeting, and prototype evaluation. An organization's design procedure and many other manifestations of the administration of design are of great importance in providing contact between designers and their organizations. What is the present practice?

Conclusions

The understanding of design is at an early stage, and a great deal of research needs to be carried out. At present, studies should be in particular fields of engineering and generalized design concepts covering many disciplines should be built up later by the comparison of results. Within one field, models or concepts are needed to define areas of study. These may be drawn up on a heuristic basis and tested by reference to appropriate committees, conferences and discussion meetings. Decisions to limit research to particular regions or levels in the field may be necessary.

Chapter 35

DESIGN SCIENCE

S.A. Gregory

Introduction

The aim of this chapter is to promote the concept of design science. This is introduced by a brief definition which is orientated towards the practical values of the subject. The principal contributing sources are then briefly mentioned. The characteristics of a science are detailed, and the scope of design is reviewed in a general manner for the purpose of revealing what appear to be fundamental concepts. The design process is then considered in terms of some of the possible models. The scope of research in design science is outlined in the Appendix to this chapter.

Design methods have been in existence in various fields at least from the time of the Greeks, and in modem times may readily be traced back to Leonardo da Vinci. In recent years, particularly in the last decade, attention has been devoted progressively to the study of general methods of design, as opposed to the study of methods of design within particular fields of technology or other relevant subject. The latter, according to the maturity of the technology concerned, might have received anything from two centuries of study, as in the case of civil engineering, down to half a century for chemical engineering, with perhaps somewhat less for electronics.

The development of specific approaches of a general nature, such as the morphological method of ZWICKY (1948) and the broad claims of the several varieties of system engineering, have emphasized the arrival of a well-defined and important branch of a field of study, itself ready for treatment by the accepted methods of science. It is probably this which caused GOSLING (1963) to write:

> '. . .it seems not unreasonable to hope that the whole discipline of system engineering may serve as a paradigm for a rational theory of design. By a rather serious restriction on the range of competence that it professes by concerning itself primarily with assembly-job flow systems in a formalized design situation it has been possible to develop a family of useful synthesis techniques. Some (such as the feasibility study and failure design) can be taken over directly into a more general context, others, (such as the heuristic theories) may need fairly radical modification, yet others (topological models, perturbation methods) may have little application in fields outside system engineering. As system synthesis and analysis techniques grow in potential it becomes profitable to try where possible to re-express other kinds of design problem in system terms. . .'

Design science is concerned with the study, investigation and accumulation of knowledge about the design process and its constituent operations. It aims to collect, organize and improve those aspects of thought and information which are available concerning design and to specify and carry out research in those areas of design which are likely to be of value to practical designers and design organizations.

For these reasons, design science has to develop its full interdisciplinary potential and take what is available, not only from the fields of systematic design and system engineering, but also from management science and those aspects of the behavioural sciences which have the possibility of throwing light on design, designers, design organizations, and the social implications of design.

Can there be a Science of Design?

First, it is necessary to recapitulate the characteristics by which a science may be recognized. There is no absolute criterion: practical scientists within a given area tend to agree at a particular time upon the features which distinguish the scientific from the non-scientific; practice sees little of the criteria proposed by POPPER (1959, 1963) which are primarily of a prophylactic nature.

According to the maturity of a science, a gradation of behaviour reckoned as scientific may be expected. This may range through:

(1) Description of phenomena (natural history phase).
(2) Categorization in terms of apparently significant concepts.
(3) Ordered categorization whose pattern may be deemed a model (the evolutionary taxonomy or periodic table phase).
(4) Isolation and test of phenomena, with implied reproducibility by independent observers (foundation of 'research').
(5) Quantification (classical physics phase).

Accompanying these will be the progressive development of models of all types, initiated by speculation, conditioned by the prevailing conceptual climate, and valued in terms of their ability to explain and then predict phenomena. Quantitative prediction provides a major influence in the reduction of uncertainty concerning the validity of a model. This is reinforced by the number of occasions of success.

As far as design is concerned, the occurrence of all these kinds of reputedly scientific behaviour may be expected. This is so because the area of study is interdisciplinary in the present academic sense. Up to this time, sciences have largely developed around topics of a restricted character, definable in terms of some material level in the physical world. The early study of medical science is, however, an example to the contrary. In general the development of the classical sciences has led to a fragmentation of human experience and potentiality, although accompanied by a deepened knowledge. Today the need is for the development of sciences covering the key interdisciplinary themes, of which design is but one.

Design science is concerned with the study of design as shown by the evidence of material objects, in the behaviour of individuals engaged in design, and in the behaviour of design groups. It is concerned with the effects and fate of the end-products of design. Design science is concerned to treat these phenomena in a manner as fully in accord as possible with the normal understanding of scientific method, and to make available the resulting knowledge and theories for the better accomplishment of practical design.

What is Design? The Product and its Behaviour

The material and inanimate evidence for the study of design, available for all to see, lies in the accumulation of artefacts, an inclusive category for the totality of products of human art and workmanship.

Within technology, groups of operations may be seen which embrace substantially the material and physical side of economic endeavour:

(1) Materials – their mining, extraction, preparation.
(2) Energy – its preparation, distribution, utilization.
(3) Shaped products – capital equipment, consumer durables, consumer goods, *etc.*
(4) Transportation – land, water, air, space, *etc.*
(5) Information transfer – printing, telecommunication, computers, replacement of man, *etc.*

A brief picture of the way in which these great branches of industry are linked together to give man power over nature is presented in *Figure 35.1*. This depicts the processes which eventually deliver material, energy, information, or some combination of these, to the consumer for his satisfaction. The processes required are designed, or have come together in the

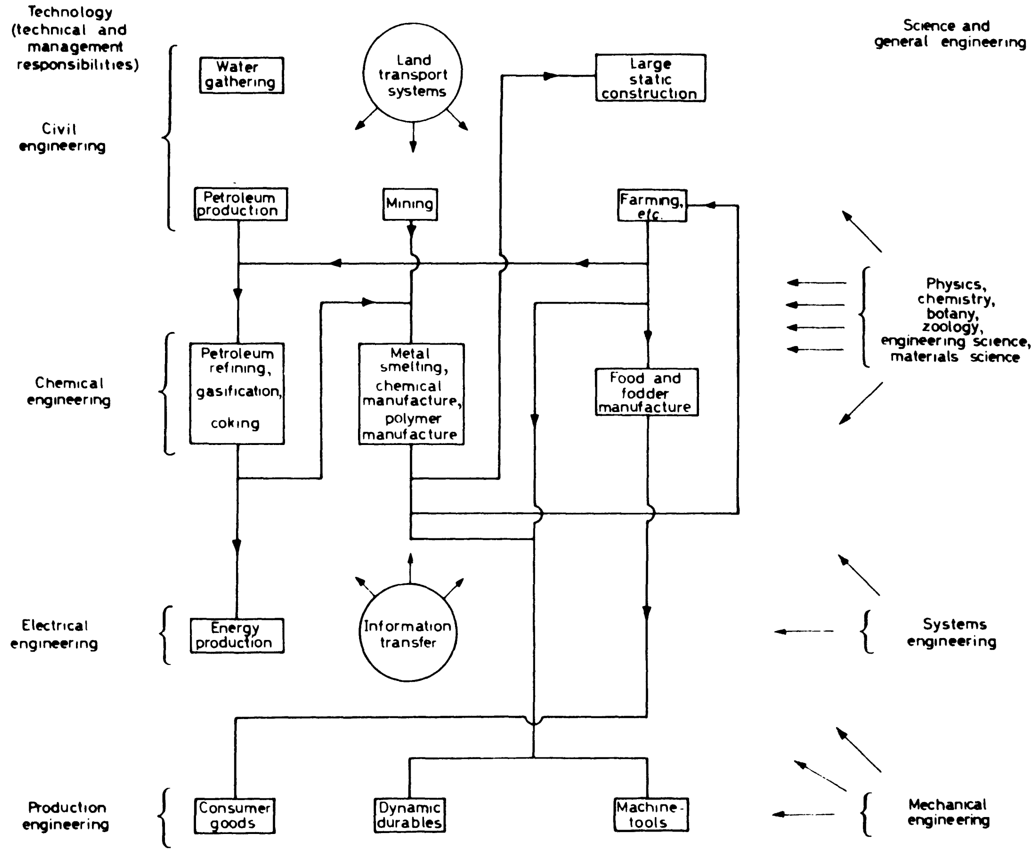


Figure 35.1. Some linkages between the great branches of industry, the technologies and the sciences

course of time, to form systems. They operate through equipment, now commonly termed hardware, which is the material embodiment of the design. The expression of the process design is through a hardware design.

The processes themselves require an abstract design and the formal statement of these comprises software. Although the obvious evidence for the work of technology is the accumulation of material artefacts, accompanied by the delivery of satisfactions, the basic and most important artefacts are abstract.

As far as processes are concerned, the material embodiments may be viewed as vessels or shapes within which the processes take place. In architecture the concern is with the construction of vessels for the operation of the living process. Apart from providing a suitable shape for the process, means have to be provided to protect the process from external interference, particularly from the effects of weather. In chemical engineering a process is designed which is carried through in interconnected pieces of plant of suitable shapes. These plant items are usually constructed in such a way as to prevent their contents from affecting the surroundings, and to avoid the influence of the environment upon the process. In telecommunication the process takes place inside suitable components, and often in selected parts of the environment, avoiding where possible uncontrolled leakage.

From these examples, material embodiment may be seen to incorporate at least two functions: the facilitation of the process by a particular shape; and the protection of the process from interference or loss.

That some distinction needs to be made between the design of the process proper and the design of the embodiment, and between the process function of the embodiment and its support or containment function, is not essentially new, although probably unfamiliar. There is part of such a distinction to be found in an article on the steam engine, published in 1853 by TOMLINSON:

> 'For about 60 years, from 1710 to 1770, the engine remained almost in the state to which Newcomen had brought it, although occupying for the latter part of that time the attention of Smeaton, indisputably the greatest statical architect of modern times. It is truly astonishing that a designer so unrivalled in the mechanism of all fixed structures, fulfilling in them the newest and boldest requirements in the very simplest ways (and moreover so ingenious and conclusive observer and experimenter on the mechanical powers, including steam itself,) should be employed on this engine. . . without seeing the great improvements for which it was now fully ready . . . It seems, however, that even between Statics and Dynamics, which are regarded as divisions of the same science, or at least between the inventive applications of each, Architecture (or Engineering as it has been called since Smeaton's time) and Machinery, the connection is not close enough for the same persons to excel in both. . .'

Given such a separation in thought, hardware design can be seen as broadly concerned either with systems involving transport or transformation phenomena, or with structures or groups of structures concerned with non-transport or non-transformation. The material artefacts involved in these may be built up from components which themselves may be systems or static units.

Since an important part of design is concerned with the delivery of satisfaction to the consumer, it is worthwhile to look more closely at specifically consumer products. Bearing in mind that, since they come into close contact with the consumer, these must be impregnated with subjective values, one may see the objective material functions, perhaps rather simply, in the following ways:

(1) Foodstuffs – stores of materials and energy.

(2) Clothing – containers for life-process units.

(3) Furniture – containers for stores such as food, books, *etc.*, or containers for life-process units for specific duties.

(4) Semi-durables – *e.g.* refrigerators, television sets, which comprise subsidiary systems needed for the life-process.

(5) Durables – *e.g.* houses, which constitute and provide space for the life-process, and which contain subsidiary systems such as water-supply, heating, *etc.* These may be directly in support of the main process or may serve to prevent interference from outside, *etc.*

Material embodiments are, by their nature, composed of materials of construction. These need manufacturing specifications in order that they may be correctly shaped. Static embodiments involve shape and magnitude; for dynamic embodiments motion must be added. Materials may also be used as feedstocks for chemical transformation, or as sources of energy. Materials may be held between stages of transformation, whether in shaping, chemical processes, or other system operation. This constitutes a store stage. For such a process an input and an output have to be specified; the condition of functioning is that no change shall occur. Storage is a zero-process but not a non-process.

For containers and supports, the essential feature is non-process. In general, at the interface between the process and the environment, there must be no process transaction, but because of the limitations of many materials of construction this limitation may have to be converted into an acceptance of an economically small leakage or loss or transformation.

It is a general characteristic of artefacts that the nearer they come to the consumer or user (this allows for machine-tools, *etc.*) the more consideration needs to be given to the interaction at the interface of the artefact or system with the human beings concerned.

Varieties of Design

Students of technological design already recognize different versions of design activity which may have a hierarchical relationship within the design-space of a system. For example, it may be a system or a component that is designed; it may be a process or a container.

Not all major practical design activity is necessarily overtly concerned with system design. Systems have the advantage that the design problem may be formulated in terms of an input–output equation:

$$\text{Output} = f(I)$$

The transfer functions symbolized by f constitute an important part of the study of the given technology (in so far as it is based upon transformations) and their determination is the foundation of a design of the type concerned. Such a system may consist of a single line; or of several systems in parallel where one may be dominant; or there may be interactions between parts of one system, or interactions between systems in parallel. Clearly, where interaction occurs, the design becomes more difficult.

For the case of non-process design, the input–output approach cannot be immediately used. In the simplest cases concerning retention of shape or position, the essence of design may be expressed by an inequality in which the force tending to change must not overcome the resistance. If the required materials which give the condition of stability cannot be found then some version of the input–output equation may have to be used. The design would normally involve a feasibility study and an optimizing study, with a possible interaction.

Design for shape may be dominated by process or stability considerations under economic constraints, or by direct geometrical constraints, or by human requirements. Some aspects of the geometry involved in design are extremely complex and design techniques or strategies are ripe for mathematical investigation, probably exploiting the computer advantageously.

A detailed study of some of the interactions between successive stages of design in a specific case has been reported by GREGORY (1964*b*). This refers to process design, process shape, container design and materials selection, and also involves an aspect of production method design.

Design Itself a Process – Possible Models of Designer Behaviour

Much of what has been considered so far, may now be exploited in the consideration of the design process itself. Design is normally taken for granted as a process and its operations described in the form of a block diagram. It is also readily assumed that design is a process which has an input and an output. Although many models have been suggested for the design process it would seem likely, in the light of the earlier discussion, that a system model is perhaps the least sophisticated model with a possibility of giving useful results. Any simpler model is likely only to have literary interest. A simple example of the latter would be to describe design as a crystallization.

According to the system model, concern is mainly with the specification of the transfer functions. If design is seen as an information transforming process, then the individual information transformations must be specified. As far as is known, by direct inspection or by psychological investigation, the number of classes of transformations is small. Scientific exploration is therefore a possibility. Design is an unsteady-state process (see Chapter 31) although occurring within almost constant designer facilities.

Together with these functions, concern must also be with storage and with the prevention of loss or interference during the process: with the conversion of abstract knowledge into embodied knowledge.

In the light of information theory it should be possible to expand the details of this model substantially. This remains as a task to be done. In this task, the designer is regarded as in the same class of machines as the digital computer and, given this similarity, there should be no reason why a computer should not carry through a design of the type which this model represents. For a closer approach to the practice of design, models with greater sophistication are needed. Watts, in Chapter 11, provided a model of an autonomic information process.

Design as a Psychological Process

The study of the behaviour of the individual designer shows a number of characteristics not revealed in the simple information process model proposed. The human designer is a very complex system with a number of lines operating in parallel, and possessing enough inherent flexibility to accommodate a variety of design programmes and to invent new ones.

The designer provides something analogous to the function of a pump in a material flow process: he has 'head' and 'capacity'. He displays that ability to provide new solutions which is called creativity. He takes decisions on values, and under uncertainty both in respect of information potentiality available now and in the future. The designer is prepared to gamble on the unknown and on his own ability. He is vulnerable to his environment. Attitudes are important.

To discuss just one of these differences, namely creativity, brings out the greater complexity of the model and, at the same time, suggests some of its values. It is possible to see the phenomenon of creativity as an interaction between the life-process and the mechanical information transformation process. It is this interaction which provides the possibility of a creative transformation at every stage of the design process, and not just at the stage commonly called synthesis. If the stages of design are set out in the form of a block diagram as a first approach to the specification of the transformations, then creativity may occur at every stage. A new perception of need or a new appreciation of value might be obtained (GREGORY, 1965).

This aspect of the model provides further opportunities for research. Already some people have developed practical approaches which are exploiting some of the possible areas of specific function creativity. For example, the 'Synectics' group has worked on the task of stating a problem in the most fruitful way (GORDON, 1961). Farradane, in Chapter 12, looks at the creative search for information. SHACKLE (1961, and earlier) emphasizes the creativity of decision.

The ambition to discover the mechanisms whereby these operations take place will be powerful. Yet the type of human behaviour discussed is likely to be well embedded in the 'black box' class, and to resist detailed analysis. What is likely to happen is that some more techniques of a practical nature will be discovered and finally it will become possible to set up some simple models by which parts of the operation may be carried out. The kind of investigation relevant to a system will be performed in which an input with suitable variations is provided and the effect on the output noted. Thence it will be possible to argue to the nature of the transformation devices. Since the input and the output will consist of information of various kinds, in any of the possible communication languages, it will perhaps be assumed (as in Gregory 1964*b*) that comparable transformations, whatever the language of communication, are produced by equivalent creativity functions. In order to obtain such a result, the use of a suitable black box may be considered, such as that described by ASHBY (1956), fitted with transducers to convert the input communication into common black box language, and to convert the output suitably. Ashby comments on the design process.

This model has many interesting implications and, like the mechanical information transformation process, still requires elaboration and detailed study.

Design as a Sociological Process

The mechanical information model and the psychological model have been looked at, and some of the possible points for further research, based on questions stimulated by these models, have been noted, but attention has been restricted to the individual designer. A model is needed which would enable a useful investigation of the execution of a design process within a working group to be made. Indeed, it is possible to look forward to composite or hybrid systems involving a number of designers and one or more computers, with other facilities.

Such a system would need a model representing a micro-sociological process, as suggested by GREGORY and BURDIS (1965).

It would be reasonable to expect that the original model of the mechanical information transformation system could be subsumed in some form within the psychological model and that this, in turn, might be subsumed within the micro-sociological model. Some of the first implications are being explored elsewhere, in terms of creativity and of decisions.

Design Situation

The design situation incorporates the opportunities for and the constraints upon the practice of design. The opportunities are those for the provision of satisfaction to the consumer and user. They are also the opportunities for the satisfaction of the designer organization. This may be in terms of the contemporary economic values, or in terms of challenge, or according to the lapped hierarchy of need-fulfilment of MASLOW (1954).

Unless the design situation is studied scientifically and the results acted upon, all efforts at the study of design in products, or of the process of design, are likely to be sterile. A systematic survey of opportunities for design in growth areas needs to be developed – generalized marketing for design – taking due regard of such pointers as the National Plan, and of critical survival requirements. The necessary profile of design capabilities should be specified, and the changes needed with time should be reviewed. One should therefore look more closely at the topics touched upon in Chapters 4–9, and repeatedly ask how existing products might be improved to meet the needs of the situation, or whether radically new approaches should be used.

Constraints will always be present. Our effort must be turned to dissolving, eroding, or overturning unnecessary constraints. These are largely in the mind, as opposed to natural constraints, and come either from idleness or misplaced enthusiasm for outworn doctrines. The scientific analysis of innovation problems, along the lines suggested by ROGERS (1962), is our hope, provided that it is followed by action.

Research in Design Science

Some areas for research have already been indicated and these are developed in the Appendix. These tend to be concerned with large, or general, or abstract topics. Principal stress has been placed upon the nature of the design process and upon the development of broad concepts which might assist the analysis of design procedures. *But consideration must also be given to research which promises to be more immediately productive. This is likely to deal with the techniques of present design, mechanical and theoretical, and with the day-to-day strategies practised in most areas of technological design.* Any organized design research must achieve some balance between the immediately useful and the fundamental, each fertilizing the other.

APPENDIX: Outline of Suggested Research Fields in Design Science

The outline is intended to be concerned with all major aspects of design and its constituent operations, in theory and in practice. First, possible topics are listed in terms of the design process; then follows a suggested allocation of such problems among existing academic disciplines.

Design – The Product, Process and Situation

(1) The Design Process – Adequate and plausible accounts of design under all conditions. Comparison of various kinds of design. Generation and exploration of concepts characterizing design. Generation of models. Evaluation of models.

(2) Establishment of Design Need – Market research. Home and export market characteristics. Short-term and long-range forecasting. Comparison of mass-production and one-off outlets, and the designs for them. The possible applications of innovation research to marketing.

(3) Values and Design – Social effects of new designs. The individual and new design. Methods of quantifying values.

(4) Methods of Approaching Design Problems – Collection of procedures and rational analysis thereof. Development of new approaches. Comparison of methods used in

various technologies and their branches. Establishment of techniques of approach appraisal. Practical comparison of alternative techniques on selected problems.

(5) Information-handling for Design – The nature of design information. Retrieval methods. Methods of generating information. The value of information and its economics. Mechanical methods of information transformation.

(6) The Production of Ideas – Collection of existing heuristic techniques. Rational analysis. Development of new heuristics. Application of computer methods. Creativity. Analysis of creative behaviour. Generation of new creativity techniques.

(7) The Communication of Ideas – Information theory and its applications in design. The channels of perception. Symbols, models and their varieties. The specification as communication. Mechanical methods of reproduction and transmission. Optical methods. Electronic methods. Economics of alternative methods of reproduction and communication. Exploration of new techniques.

(8) The Testing of New Ideas – Abstract models. Drawings. Concrete models. Analogues. Pilot plants. Prototypes. Levels of certainty.

(9) Decision-making and Decision Strategies – Adequate accounts of decision-making in design under all conditions. Generation of suitable models. Psychological tests. Possible selection procedures.

(10) Materials and Design – Relationship of materials to design, including transformation properties, protection and support, production implications. Materials selection procedures, their collection and rational analysis. Development of computer methods of materials selection. Exploration of material possibilities and probable effects on design. Study of major materials limitations in existing design. Reliability and its relationship with material properties.

(11) Man–Machine Interaction – Ergonomics and design. Safety. Aesthetics.

(12) General System Design Problems.

(13) Management and Design – Methods of improving design productivity. Effect of existing general management techniques. Measures of design output and efficiency. Possible new methods of increasing productivity. Effects of the design environment. Methods of stimulating creativity.

Possible Allocation among Disciplines

(1) Philosophy – Study of the key concepts of design. Problems of value. The nature of optimality, novelty, uncertainty. Investigation of areas reputedly deficient in concepts. Conceptual change.

(2) Mathematics and Computer Science – Optimization techniques. Studies of spatial arrangement. Studies of heuristic devices and heuristic programming. Development of computer methods of executing tasks now undertaken manually. Communication investigations.

(3) Physics and Electronics – Optical methods of reproduction. Electronic methods of reproduction. Hybrid methods of reproduction. Optical and other methods of shape manipulation.

(4) Materials Science – See earlier heading Materials and Design.

(5) Engineering Technologies – Development of specific design techniques. Development of general system design techniques.

(6) Economics – Marketing and design. The economic values of design. The economics of information in design. Economic techniques in design.

(7) Psychology – Psychology of the designer. Involvement and motivation. Attitude and design. Creativity. Selection procedures for designer choice. Psychology of the user. Ergonomics. Psychology of the purchaser. Problems of innovation. Behaviour in uncertainty.

(8) Sociology - Behaviour of design groups. Innovation problems of design. Study of social demands for design.

(9) Management Science – Exploration of specific management techniques as applied to design activity. Studies of companies and their design procedures in relationship to successful company operation. Studies of design productivity.

GLOSSARY

Algorithm. A routine or device for calculating. The algorithmic approach becomes more general in methodical procedures for design. The present-day significance of the algorithm lies in its potential use in a computer programme.

Artefact (artifact). A product of human art and workmanship; the material result of designing; anything which has been designed and manufactured.

Autonomic. Having the right of self-government, of making decisions. A designer who is not autonomic to some degree is not a designer.

Concept. A general notion. In normal parlance this conveys the idea of a class of objects, whereas for a designer it implies the first outline of an artefact, whether in the mind or as a sketch, which needs further details for a satisfactory specification.

Constraint. A limitation, usually of a compulsory nature. In facing constraints a designer is limited or confined in respect of choice. Some constraints are natural, *e.g.* the limit in strength of a material; others are social; still others spring from the individual.

Creativity. The ability to respond in a novel and useful way to a problem. Creativity can only be seen after the event. Tests of creativity are concerned with disclosing what is believed to be potential creativity in an individual regardless of circumstance.

Decision. A choice between alternatives which settles a course of action.

Ergonomics. The study of the relation between man and his occupation in terms of anatomy, physiology and psychology, and their interaction with the characteristics of working equipment and environment.

Function design. The central part of design which is followed (if it is not a mechanical function) by mechanical and production design.

General systems theory. A theory developed over the last decade in an attempt to comprehend the significant aspects of all classes of material objects having structure. General systems theory is essentially concerned with levels or hierarchies of behaviour which are related in some way to the complexity and machinery of the objects concerned. For example, fundamental particles come together in atomic nuclei. Upon these, suitable development of electron shells provides the chemical basis of atomic behaviour. Atoms combine to form molecules. Molecules of sufficient complexity and adequate chemical properties come together to form living cells. For the designer there is a hierarchical series of classes of artefact, starting with a static mechanical piece. Such pieces may be formed into a static structure. A structure may be caused to deflect or vibrate. Other static pieces may be formed into a structure capable of transmitting motion by rotary or other movement. The addition of other pieces makes it possible to control the speed or motion of the structure. Structures may be developed to convey or transform electrical impulses, or the structures may be used to house chemical reactions. By the suitable accretion of devices, complex artefacts may be constructed which will contain living material, or which will carry out sophisticated logical operations, or simulate self adaptive behaviour. The aim of general systems theory is to characterize the principal patterns of systems structure and to provide an account of the underlying logic.

Graph theory. See *Network.*

Heuristic. Having to do with finding; related to improving problem-solving performance; relying upon problem-solving devices which appear to be particularly relevant to the circumstances and, if need be, devised for the occasion; a mode of procedure held to be necessary in the absence of satisfactory algorithms. Heuristic procedures move from the use of known methods to novel methods. Creativity techniques are attempts to stimulate heuristic behaviour.

Iconic. Of the nature of a representation.

Innovation. Making changes or bringing in novelties. In the sociological sense innovation concerns the processes of communication and adoption of products or techniques.

Methodical procedure. Orderly or regular arrangement to procure a result. An algorithm is a methodical procedure for calculation. In design a methodical procedure normally conveys the notion of a programme which may be written down and subsequently used by someone unskilled. Most design involves some further element and the methodical procedure may be seen as a device for making skill more available to the difficult areas of design. This kind of procedure may involve a sequence of strategies.

Methodology. A study or extended development of method in some sphere of activity.

Model. A representation of some past, present, or future object or event, used for communication or for dealing with problems. There may be a considerable degree of transformation between the representation and that which it represents.

Morphological. Having to do with the study of form. In the field of design the word refers particularly to the approach of Zwicky (1948) to analysis and construction. If some well-defined characteristic is involved, a schematic representation of the totality of possible occurrences of the characteristic is arranged in a 'morphological' box or manifold. Completeness of the manifold is achieved if no compartment contains more than one occurrence. Some compartments may be empty. The object in each compartment is evaluated in the light of the original requirement. The morphological method is primarily a search procedure.

Network. An interconnecting set of points or items in two or three dimensions (*n* dimensions are not ruled out). This network may be represented by a network of lines and points drawn on paper or constructed in three dimensions. Such a network may be random or ordered, may be richly connected, or may divide into successive branches like a tree.

Such a network may represent material or abstract relationships. A static network may represent relationships in a general manner or imply some sequence in value or time. Also, the lines may imply some specific orientations in space and, in addition to direction, may indicate length and other factors such as capacity. Flow of some kind may occur and such flow may be steady or unsteady. Portions of the network may move relative to each other. Their interconnections may remain the same or change.

The study of structures of this type, the study of relationships, is clearly a general way of looking at some of the fundamentals of systems.

Objective. The point or goal towards which operations are directed. Policy is the set of principles underlying a course of action, declared or implicit, determined to achieve an objective.

Opportunity. Opening for the exercise of enterprise in any kind of activity; with reference to design, changes in the market, technical skill, or productive capacity, provide openings.

Optimization. Improvement in performance, preferably to the useful limit, as gauged by some agreed relevant standard of value.

Paradigm. Example or pattern; a normative model.

Precedent. Previous design taken as example for subsequent work. A successful precedent carries a level of justification.

Product. That which is produced either in the course of nature or by manufacture. Today it is normally used to represent something designed, made, and offered to a consumer. Within design there are also special meanings.

Realization. Conversion of a plan into fact. The realization of a design involves the completion of mechanical design, its detailing or specification in terms of fabrication in some selected material, the production of these items, their assembly, test, and commissioning, and the overall organization of these operations.

Restraint. See *Constraint.*

Satisfaction. The fulfilment of a want or need by sufficient supply.

Set theory. A species of logic dealing with the relationship between discrete objects or points in terms of the groupings to which they may belong. The theory is considered fundamental to modern mathematics.

Situation. The total circumstances in which a design is prepared and a product made, marketed and used. The designer attempts to bring about a match between the needs of the situation and the characteristics of the product. The function of marketing is to gauge the opportunity presented by the situation.

Strategy. A pattern of action aimed to achieve an objective. Design strategies are usually concerned with making the most effective use of design skill in complex situations. A strategy has to be directed generally towards the objective and must lie within the policy bounds. Because of unknown territory ahead, a strategy may not be successful. A strategy may contain a succession of sub-strategies developed by study of the relationship between means and ends at successive stages in the operation.

System. A word having a number of meanings relevant to design. The first dictionary definition usually suggests: complex whole, or set of connected parts or things; organization of material or immaterial things. It is this meaning which is stressed since it has a double relevance to design. Design itself is concerned with the conception, production, and arrangement of parts or things in some relationship having value. Furthermore, some members of the class of systems, as seen in general systems theory, have considerable engineering and economic significance. The behaviour and mode of design of such systems have been studied in some detail.

System design and engineering. The design of systems of the type mentioned above. Such systems are concerned with the transformation or transport of mechanical energy, electrical energy, chemical materials, or information. In many practical systems there may be considerable interaction with humans.

Systematic procedure. See *Methodical procedure.*

For further definitions, see also Chapters 3 and 32.

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(The general references given above also deal with most aspects of the environment in reasonable detail.)

NAME INDEX

See also References and Bibliography

SUBJECT INDEX