THE DESIGN OF

ENGINEERING PRODUCTS

by

William Powell Lewis,

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of

Master of Engineering
1 INTRODUCTION

1.1 SCOPE OF THESIS
1.2 DEFINITION OF ENGINEERING DESIGN
1.3 OBJECTIVES OF ENGINEERING DESIGN
1.4 CLASSIFICATION OF ENGINEERING PRODUCTS
  1.4.1 General
  1.4.2 Classification Based on Design
  1.4.3 Classification Based on Manufacture
  1.4.4 Classification Based on Use
  1.4.5 Comments
1.5 IMPORTANCE OF ENGINEERING DESIGN

2 FUNDAMENTALS OF ENGINEERING DESIGN

2.1 INTRODUCTION
2.2 NATURE OF DESIGN
  2.2.1 Structure of a Design Project
  2.2.2 The Design Process
  2.2.3 Decisions in Engineering Design
2.3 PRODUCT PLANNING
  2.3.1 General
  2.3.2 Programme for Product Planning
  2.3.3 Comments
2.4 CREATIVITY IN ENGINEERING DESIGN
  2.4.1 Introduction
  2.4.2 What is Creativity?
  2.4.3 Creative Thinking
  2.4.4 Barriers to Creativity
  2.4.5 Creative Engineering
2.5 COMMUNICATIONS IN ENGINEERING DESIGN
  2.5.1 Input of Information to the Designer
  2.5.2 Output of Information from the Designer

3 THE ENGINEERING APPROACH TO DESIGN

3.1 INTRODUCTION
3.2 MATHEMATICAL MODELS AND ARCHETYPES
3.3 PLANNING A MACHINE SERIES
  3.3.1 General
  3.3.2 The Basis of the Plan
  3.3.3 The Number of Models in The Series
  3.3.4 Planning a Series of Gearboxes
  3.3.5 Planning a Series of Centrifugal Pumps
  3.3.6 Conclusion
3.4. OPTIMUM DESIGN
3.4.1. General
3.4.2. First Statement of the Optimization Problem
3.4.3. General Statement of the Optimization Problem
3.4.4. Optimum Design of Mechanical Elements
3.4.5. Conclusion

3.5. RELIABILITY
3.5.1. Introduction
3.5.2. Definitions
3.5.3. Factors Affecting Reliability
3.5.4. The Mathematics of Reliability
3.5.5. Improvement of Reliability
3.5.6. Conclusion

4. ECONOMICS OF ENGINEERING DESIGN
4.1. INTRODUCTION
4.2. DESIGN POLICY
4.2.1. General
4.2.2. Variety Control
4.3. CONTROL OF COSTS DURING DESIGN
4.3.1. Standardization
4.3.2. Tolerances
4.3.3. Value Analysis
4.3.4. Programmes for Cost Control

5. REVIEW OF ENGINEERING DESIGN
5.1. GENERAL
5.2. THE DESIGN ENGINEER

BIBLIOGRAPHY

FIGURES
This thesis examines the design of engineering products. Its purpose is to clarify the role of design in engineering, to give a general description of the design process, and to emphasise aspects of the subject which are not widely recognized, or if recognized are not applied in practice because of the designer's preoccupation with the rush of day-to-day problems.

Parts of the thesis inevitably reflect a bias towards the author's experiences as a mechanical design engineer in privately owned industries where the products were manufactured in small or medium-sized batches. This bias is most clearly evident in chapter 3, but also appears in sections of chapters 2 and 4. All in all, a broad perspective has been adopted with the intention that the thesis should cover a wide range and not be confined to the interests of a special branch of engineering. For this reason the word "engineering" in the title has not been qualified in any way.

After giving considerable thought to this subject the author came to the conclusion that there was scope for bringing together in one paper the ideas and concepts which are of major importance in engineering design. All too often these are not appreciated by the individual designer, because references to them are widely scattered throughout the literature or because he allows himself to be immersed in the minutiae of his work.
CHAPTER 1

INTRODUCTION.

1.1 SCOPE OF THESIS

Engineering design is a human activity directed towards the manufacture or construction of products which fulfil human needs, in particular those needs which can be met by the application of engineering technology. The word "product" is here used in its widest sense; at one end of the scale it includes complex systems such as dams and power stations, and at the other end simple articles such as doorknobs and hinges.

The first chapter introduces and defines the subject and discusses the purpose of engineering design, its objectives and their relative importance. The role of design in engineering and the work and responsibilities of the design engineer are then established. A designer does not usually produce the goods which satisfy consumer needs. The immediate purpose of design is the preparation of a model or template so that the product can be reproduced as many times as required. There are many types of product and it is a valuable exercise to classify them so that the designer can have a better appreciation of his own work and where it stands in relation to other engineering designs. Several useful classifications are given later in this chapter.

Chapter 2 considers the work of the design engineer by analyzing the flow of information to him and the means by which he selects, combines, and organizes this information in order finally to communicate a description of the product to those responsible for its manufacture or construction. This chapter attempts to answer questions such as — what information does the designer require and how does he use it? How is a problem stated for him and who does that?

Engineering design is distinguished from other design activities by the extent to which technological factors must contribute to its achievement. Chapters 3. and 4. discuss some factors which are of fundamental importance to engineering design, and which are especially relevant to the design of economical and reliable products. The last chapter summarizes the main points which emerge from this investigation and the conclusions to be drawn from it.

It is not intended in this thesis to consider the specialised knowledge which is required for specific design projects, rather to concentrate on those principles which belong to a general theory of engineering design.
1.2 DEFINITION OF ENGINEERING DESIGN.

Design is the essential purpose of engineering. It begins with the recognition of a human or social need which is to be satisfied by the application of science and technology. An idea is conceived to meet this need, the problem is defined in engineering terms and a programme of directed research and development undertaken leading to the construction and evaluation of a prototype. The process continues with the effective multiplication and distribution of a product so that the original need may be met wherever it exists. The object of a design is some material good or service which has a utility to the consumer that equals or exceeds the cost of making it available to him.

The heart of engineering is design and synthesis, not merely the analysis of the relationships between different parameters. The engineer works in situations where there are no single, correct answers, and where deciding whether a design is sound and acceptable depends often upon his judgment and the evaluation of statistical factors. In the final analysis every engineering problem is one in probability; a real-life problem cannot be stated with exactitude and the operation of all its parts cannot be predicted with perfect accuracy. The engineer has to design so that the performance and appearance of the product lie within an acceptable range and so that it has an acceptable probability of working. In engineering the design problem may involve numerous approximations and a combination of experiment, theory, simulation, and test in order to choose the proper weighting of the various factors affecting the design.

A design must suit its environment, the people and other equipment with which it will be associated in service. Engineering design almost always requires a synthesis of technical, human, and economic factors; and it requires the consideration of social, political, and other factors whenever they are relevant.

1.3 OBJECTIVES OF ENGINEERING DESIGN.

To establish the objectives of design it is first necessary to understand the relation between a design and its environment. Clearly engineering design must be affected by current technological advances, economic conditions and, on a wider scale, by the social, political, and other cultural factors which are present in the society in which we live. In its turn, society may be affected by the consequences of a design project. The relations between engineering systems and their environment will now be studied in greater detail in order to throw light on those demands of society which bear on the designer.

One of the main patterns of the human social system is the production-consumption cycle, illustrated in fig. (1.1). Industry produces and commerce distributes the goods and services that people consume. After consumption is completed the waste products are removed; usually they are destroyed but sometimes they are salvaged. The four main processes in this cycle are:
(a) Production
(b) Distribution
(c) Consumption
(d) Recovery or Disposal.

As resources become scarcer it becomes more important to recover the end products of human consumption rather than to destroy them.

Engineering products enter this production - consumption cycle and move around it; they must therefore be designed to be compatible with the four processes of which it is composed. Since each process places its own set of demands on the design and these demands are often contradictory, reconciling the conflicts which arise is one of the principal problems facing the designer.

To a large extent the engineer designs for the consumer who must after all show his acceptance of the product by purchasing it. However, the designer also has to take into account the views of the producer, who is usually his employer, and those of the salvage-operator. Now to meet the requirements of the consumer the general objectives of the design of an engineering product are:

(1) Performance
(2) Appearance
(3) Cost.

The product must accomplish the primary function for which it has been designed, its appearance must satisfy the aesthetic feelings of the consumer, and its cost should be the minimum value compatible with an appropriate level of quality of performance and appearance. As explained above, the designer must consider the demands imposed at the various stages of the production - consumption cycle; these are set out below.

(a) Consumption.

To ensure that the product is of sufficient utility to the consumer some or all of the following factors may be important.

1. Ease of handling and installation.
2. Ease of operation.
   This covers the suitability of the operating characteristics of the product, such as its quietness, sensitivity, stability, compatibility with environment.
3. Ease of maintenance.
4. Durability, long service life.
5. Reliability, low maintenance costs and short down time.
   To achieve durability and reliability, the product and its components must be designed to resist their operating environment, i.e., they must not break or undergo excessive deformation nor must their surfaces be damaged. This implies resistance to any applied forces (whether steady loads or fatigue or creep or impact loads) to give strength and rigidity; it also implies resistance to corrosion, erosion and wear.
6. Efficiency, low operating costs.
7. Lightness, low weight.
8. Smallness, small volume, floor space, or frontal area.
10. Flexibility of design to allow modifications to meet special consumer needs.

(b) Production.
To ensure that the cost of production is as low as possible the designer has to consider the following.
11. Ease of production.
The design should be as simple as possible, and suit the planned production rate and production methods.
12. Use of available resources.
13. Standardization of parts and methods.
14. Reduction of rejects and scrap.

(c) Distribution.
15. Ease of transport.
16. Suitability for storage.
17. Suitability for display.

(d) Retirement of Product.
18. Matching of physical life and service life.
19. Replaceability, either of the complete product or its short-lived components.
20. Recovery of re-usable material and long-lived components.
A product may be taken out of use or retired because of its technical obsolescence, or its physical deterioration, or because of a change of fashion. An ethical question arises here - is it right to induce the retirement of engineering products such as motor cars by changing the fashion when these products are still working well and are not obsolete? While the answer to a question such as this has to be supplied by the whole community the designer cannot escape some measure of personal responsibility.

We have been considering the movement of engineering products through the cycle of production, distribution, consumption, and recovery or disposal. Now there is a continuous change in the value of the product as it progresses around this cycle. Initially there are the resources available in the form of raw materials, energy, productive facilities, and human effort, and a certain amount of these are used in making the product. This amount can be measured in objective terms and is the cost of production, so many pounds, shillings and pence. When the product leaves the producer it has a higher value than this, the increase representing his profit which in a capitalist society is the economic driving force which motivates the enterprise. There may be a further increase in value through the process of distribution arising from additional expenditure of human effort and from more favourable time and location in marketing. The final value assigned to the product is its selling price to the consumer, and at this stage it is still possible to make an objective measure of value in monetary terms.
The consumer buys the product because it has a greater worth to him than the purchase price. However, his measure of value is a subjective one, sometimes referred to as "utility." Thus the designer by using his intuition or judgment has to try and estimate the utility of the product to the prospective consumer. But the lack of an objective measure means that his decisions are not closely constrained, and a wide variety of design decisions is inherently possible.

In recent years the ideas and methods of "Value Engineering" have been developed to try and overcome this subjective element. The value of a product to a consumer is then defined as the sum of its "use value" and its "esteem value". The "use value" is the lowest cost of providing for the performance of the desired function at the desired level of quality, and the "esteem value" is the lowest cost of providing the appearance, attractiveness and other features wanted by the consumer but not essential to the successful performance of the product. The value of a product, that is its utility to the consumer, is then the minimum amount of money which must be spent in purchasing a product with the appropriate "use" and "esteem" factors. A design engineer must constantly check his work to see that what he designs contributes value to the product, either "use" or "esteem" value. Anything that contributes cost without proportionate value must be rigorously excluded from the design.

1.4 CLASSIFICATION OF ENGINEERING PRODUCTS.

1.4.1 General.

The products manufactured or constructed by an engineering organization can be classified according to features of their design, manufacture, and use. It is desirable to make these classifications in order that the designer may better appreciate where his own work stands in relation to engineering design generally. Moreover, it is essential that the management of a design group recognize these features so that the total effort of the group can be directed most effectively.

1.4.2 Classification Based on Design.

The most important characteristic of a design is its "innovational content", that is its newness, the degree to which it departs from previously established practice and enters new fields. Clearly a project of high innovational content places great demands on the designer's powers of analysis and imaginative thinking. The technical risks facing him may be very great, even transcending the bounds of private interest and involving the well-being or prestige of the nation.

Engineering products can be classified in the following order depending on the innovational content of their design.

(1) Products on the frontiers of engineering, making use of the results of a continuous programme of engineering research and development, for example, spacecraft, rocket engines, advanced nuclear reactors.
(2) Products developed from an invention or scientific discovery. Examples are: the wireless set developed from Hertz's discovery of radio waves; rotating electrical machines developed from Faraday's discovery of electromagnetic induction. Of course, as development proceeds and more products are built, experience is accumulated, the state of the art advances and the innovational content declines.

(3) Products developed to fulfil new social needs. Examples here are domestic appliances such as air conditioners and dishwashers which have been specifically developed to cater for the human desire for greater comfort and freedom from tedious jobs.

(4) Products new to the organization but already being successfully designed elsewhere, perhaps by a competitor. For example, a company designing and manufacturing washing machines might branch out into domestic refrigerators as part of a policy of diversification.

(5) Products representing an addition to an existing range or type. For example, a motor manufacturer might decide to expand his product line by introducing a new size of motor.

(6) Redesigns of existing products. It is possible to distinguish between the complete redesign of a product and modification to part of an existing design, the innovational content being at its lowest level in the latter case.

In this classification it is clear that groups (1), (2), and (3) have a high innovational content in design. As we move down the list this content becomes progressively less, the state of the art is more highly developed, and an engineering organization must then assess its designs carefully to ensure that they provide some extra in performance, appearance, or price to attract the customer.

With regard to the sixth of these groups, it is evident that many products undergo regular cycles of design, manufacture, test, and use, then redesign in the light of the user's experience in the field and to take account of any new competition or change in fashion. This process of "design by evolution" reduces the risk of major error as only relatively small changes are introduced during each design cycle. It has been a characteristic of many products which have evolved over a long period of time that the challenge of competition has been met mainly in the market place, the designer has been shielded by the salesman. Today the pace of technological change is constantly increasing and more and more scientific discoveries are becoming available for use by engineers; the range of competitive action has widened and now includes the design office and development laboratory. The gradual and unhurried improvement of a product is now less likely to meet the demands of competition. Following a scientific discovery a new body of technical knowledge develops rapidly, the proper use of which may dictate an almost complete break with past practice. There is therefore an accelerating trend towards "design by innovation".
1.4.3 Classification Based on Manufacture.

It is possible to classify engineering products according to the rate at which they are manufactured. This is done below, and it should be noted that consideration is confined to products manufactured as discrete units; as the title of this thesis implies, articles produced by continuous or flow methods lie outside the scope of the discussion.

(1) Jobbing production.

Many special-purpose products are designed and manufactured as one-off jobs, e.g. paper-making machines, oil refineries, bridges, 20,000 h.p. motors, and so on. Other products, while not ordinarily of this high degree of specialty, may be sufficiently special at least to the manufacturer concerned to be produced on a one-off basis or in very small batches.

(2) Batch production.

A wide variety of products are produced in batches either to meet specific orders or to be held in reserve as stock. Electric motors are a typical example, being produced in small, medium or large batches depending on their power and speed. In Australia, 50 h.p. 2900 r.p.m. motors are produced in small batches of 10 to 20 while fractional horsepower motors are made in large batches of five hundred or more.

(3) Mass production.

Products required in the largest quantities are mass produced, cars and household appliances being good examples.

The distribution of manufacturing costs varies with the quantity being produced and the method of production used. When quantities are low the development cost of a new product is a high proportion of the total cost, and expenditure on tools and engineering refinements nets less return in cost reduction. As the quantity of products increases, the emphasis shifts to the reduction of overheads and labour and material costs. When quantities are high an expenditure of engineering effort which results in reduced labour and material costs will give a large return for even a small saving per unit.

1.4.4 Classification Based on Use.

Engineering products can be classified into the following groups according to the manner in which they are used.

(1) Consumer products, such as cars, lawnmowers, electrical appliances.

(2) Commercial equipment, that is equipment which is used to provide a service to consumers, for example, office furniture and machines, petrol pumps.

(3) Capital goods, machines and structures associated with the generation and transmission of power, storage of water, processing of metals, chemicals, foods, and so on.
Some general trends can be observed in the designs of these different classes of product and are noted here although no attempt is made to lay down hard and fast rules of design.

<table>
<thead>
<tr>
<th>Class of Product</th>
<th>Importance in design of</th>
<th>Extent to which form is controlled by functional necessity</th>
<th>Extent to which components are designed to fill up space</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Consumer Product</td>
<td>Performance</td>
<td>Appearance</td>
<td></td>
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<tr>
<td>2. Commercial Equipment</td>
<td></td>
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<tr>
<td>3. Capital Goods</td>
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1.4.5 Comments.

To conclude this brief discussion of the classifications of engineering products, it should be pointed out that the concept of innovational content can be extended to cover the processes of production and consumption as well as design. In fact at every stage in the planning and development of new products very careful consideration must be given to all aspects of their innovational content. This applies not only to the management of privately owned companies but also to the controllers of government engineering departments. The correct evaluation of new features requires much skill and experience if shareholders' or taxpayers' money is not to be wasted. Designs of well-developed evolutionary products can have an unexpectedly large innovational content, which if not appreciated may lead to failures, witness the use of B.S.968 steel in the King's Bridge in Melbourne.

The cost of making a new product will clearly depend on the degree of manufacturing innovation, on any new or untried methods of production. In cases where engineering performance is vital, the design of a new product may be governed solely by the necessity of meeting the specified performance, no consideration being given to suiting the design to possible methods of manufacture. Thus after the turbine blade in Sir Frank Whittle's early engines had been designed special machines tools had to be developed for finishing the blade surfaces.

Innovation in use may also be important, particularly if the consumer has to make a psychological adjustment or change his previous mode of thinking about a product. For example, a consumer may resist the successful application of a new product if he has to learn new methods of operation and his previous skills become redundant.
1.5 IMPORTANCE OF ENGINEERING DESIGN

Today the fundamental importance of good design in engineering hardly needs to be stressed. In private industry, for example, most companies have equal access to similar raw materials and methods of manufacture, and in our affluent Western society consumers are becoming more and more appreciative of good design. For these reasons a company's competitive position depends more and more on the quality of its design, and an imaginative and inventive designer is a very valuable asset. Yet even now one can point to companies who have been content to live on their reputation and are using designs essentially the same as those of ten, twenty or more years ago. However, we are now living in a competitive and fast-moving world and the rewards for industry must be earned by hard work, intelligence, and effort.

Australia's external trading deficit is currently running at the rate of £100,000,000 to £150,000,000 per year and our overseas balances are only maintained in a healthy state by the large inflow of overseas capital being used to finance new projects. The need to increase our exports is therefore obvious and exhortations to Australian industry to export more manufactured products have become familiar. As has been pointed out by a number of leading authorities, a large proportion of Australian industry manufactures to overseas designs under licence agreements which forbid the sale of the end products outside this country. Thus too great a dependence on overseas licences restricts our ability to export; it is therefore necessary for Australia to encourage and develop her own designs. The importance of this is clear when it is realised that this country pays out £50,000,000 to £60,000,000 annually in royalties and licence fees. Of course, some of this money represents the purchase of know-how, special designs and techniques which would make too great a demand on our limited resources to develop here. While precise statistics are not available it can nevertheless be confidently stated that much of this money is being spent on designs of no particular merit which could be executed in Australia with great advantage.

A company manufacturing engineering products must adopt a consistent, integrated approach to design, and to achieve these four conditions must be satisfied. First, design should be treated as the responsibility of top management since an effective design policy must stem from the top. Secondly, the designer should earn a status in the industrial team commensurate with his duties and should be paid accordingly. Thirdly, design should be regarded as a long-range, continuing process, not just a stop-gap operation, so that the company always has new designs "in the pipeline" ready for any change in technology or consumer's needs. Finally, design should be treated as an indivisible whole, so that it visibly permeates all the activities of the company from plant to product, from head office architecture to point-of-sale promotion. The advantages of a coherent, instantly recognizable handwriting on all products are obvious.
Having examined the importance of design to the nation and to industry let us now turn to consider the design engineer in person. For too long, it is submitted, designers have lacked appreciation and recognition by industry. A designer needs to be thoroughly conversant with manipulative processes and materials of all kinds as well as with the results of relevant research. He should be able to use modern design tools such as computers and to appreciate cost and time factors. The designer is a creative person who works in the realm of shape and size, where proportions and movements are determined both by engineering and aesthetics. This is a type of work which requires the high intellectual capability expected from professional engineers.

Besides his immediate duty to his employer the design engineer has other less easily defined, more intangible responsibilities to society at large. Especially is this true with regard to safety. When designing a potentially hazardous product to be widely used by the public, the engineer is faced with the moral dilemma of evaluating the optimum, if not the maximum, he can provide in safety against the cost of achieving that objective. The public, nevertheless, seems willing to accept some risks. For example, in the case of air transport the law cannot attempt to protect one passenger against every risk without closing the frontiers of progress.

The engineering profession has a moral obligation to provide for public safety. This may reduce performance or increase costs. The business executive or engineer turned executive has the prime responsibility of seeing that his organization compensates its owners for the financial risks they have undertaken. The cost of safety is ultimately borne by the public in the price of the product, so that the engineers or executives who make the decisions find themselves in the uncomfortable position where responsibility for protecting the public is challenged by the realism of staying in business.

People may live or die on the basis of decisions made by design engineers or by the supervisors to whom they report. The pressures which militate against safety - the urgency to meet a design deadline, fear of competition, production problems, financial commitments - all tend to distract the engineer from his responsibilities for the safety of the public. The engineer with a conscience and sense of public responsibility will meet many occasions and situations where his convictions and principles will be put to the test. A thorough study in depth of the total cost of risk in terms of insurance, lost revenue, legal expenses, public acceptance, and other losses has never been made. It might help alter the emphasis often placed on performance and assist the engineer in resolving his dilemma.

The design engineer not only knows more than the layman about the hazards with which he is dealing, but he also has to decide whether or not to accept them. He differs from the scientist whose main responsibility is the uncovering of new knowledge; the engineer determines which of this knowledge shall be used. Acting as a judge in the best interests of
society, he must decide according to his conscience and code of ethics what these interests are and how to satisfy them. His dilemma becomes a difficult one: the prevention of injury versus the other satisfactions that the public or society demands. These considerations arise in their most acute form in the field of transport, particularly air transport, but they often occur elsewhere, for example in the selection of design stresses in high-speed rotors or in bridges.

The responsibilities of the design engineer extend beyond the immediate confines of the industry in which he works to the community and the nation.
CHAPTER 2.
FUNDAMENTALS OF ENGINEERING DESIGN

2.1 INTRODUCTION

This chapter considers some of the fundamental aspects of engineering design, the characteristic structure and methodology common to all design projects. The subject is treated from a broad viewpoint and much of what follows applies equally well to less technical design. An investigation is then made into three related topics of special interest to the engineer.

(1) Product planning - the preliminary activity which controls the input of data to the designer regarding the products he is to design.

(2) Creativity - the mental processes by which the designer arrives at solutions to the problems he encounters.

(3) Communication - the supply to the designer of the information he requires for the creation of new designs, and the communication of the completed design to those responsible for physically reproducing it.

2.2 THE NATURE OF DESIGN

2.2.1 The Structure of a Design Project

A design project is a continuous progression from the abstract to the concrete, in which ideas about needs are transformed into engineering prescriptions for turning suitable resources into useful, physical objects. As a project is initiated and developed, it passes through a series of phases; in general a new phase is not begun until the preceding one has been completed, although sometimes final details have to be attended to while the next phase is in progress. This pattern of events is common to all projects and imparts a vertical structure to design in which the major phases are:

(1) The Feasibility Study
(2) Preliminary Design
(3) Detailed Design.

Fig. (2.1) shows diagrammatically the stages through which a design project progresses. While these are set out in chronological order, it should be realised that design is too complex a process to admit of an uninterrupted progression. New information is constantly being developed by the design work itself which was previously either overlooked or unknown. The new information obtained in one stage of design often affects the validity of the work in preceding stages, which then have to be re-examined and re-worked until confidence in their results is restored. Design is essentially an iterative process.
(1) The Feasibility Study.

The starting point of a design project is a hypothetical need which must be established with sufficient confidence to justify commit­
ment of the funds necessary to explore the feasibility of developing the
means of satisfying it. An analysis of needs is performed to determine
whether society will recognize the need and pay for its satisfaction.
The results of this analysis are set out in specifications of the desired
outputs of the product. The next step is to explore the design problem
engendered by the need to give it a technical formulation and to identify
its elements - parameters, constraints, major design criteria. The
resultant engineering statement of the problem must be sufficiently
relevant and contain adequate detail to permit the ensuing steps of the
design.

After the design problem has been stated in engineering terms,
ideas are conceived, design concepts established as possible solutions.
It is this synthesis which is most characteristic of design, and it more
than any other step requires inventive and creative effort; creativity
is therefore a vital ingredient of engineering design. As with other
steps there is a feed-back, the solutions which are conceived and matched
against the background of the problem statement yield new insights and
items of information about the problem itself which may then be restated.

When a set of possible solutions has been obtained, they are
evaluated in order to discard those which are not usable and to determine
finally a set of useful solutions. Solutions which are not physically
realizable are first eliminated, then those which are not economically
worthwhile, i.e. of insufficient value to the consumer to repay the
efforts of the producer and distributor; finally, those are eliminated
which are not financially feasible because the financial resources for
their successful prosecution are not available.

The Feasibility Study is the first major phase of a design
project. It establishes whether the problem posed by the project is
soluble, whether there are any potentially useful solutions, and the
general form of these solutions.

(2) Preliminary Design.

Preliminary Design starts with the set of useful solutions
developed in the Feasibility Study. Its purpose is to establish which
of the preferred alternatives is the best design concept to serve as the
framework for the detailed design which follows. The first step, there­
fore, is to compare the several useful solutions in order to make a
provisional selection of the best concept. In principle this requires
a straightforward comparison of the advantages and disadvantages of each
solution. In practice there are several reasons why it is difficult to
make this comparison and decide on the best concept at that stage. Values
have to be assigned to factors which are often intangible and depend on
the designer's judgment; moreover, it is not yet known in detail how any
one design concept will be finally worked into a description of the product,
nor what additional design problems will arise during this process. The
factors affecting decision-making in design are further discussed in section (2.2.3) below.

The selected design concept is then expressed in some communicable form. In engineering, this will consist of layout drawings or sketches together with a symbolic description of the idea in mathematical terms. The symbolic description enables the designer to use information about the concept in order to anticipate analytically the behaviour of the prototype. It is thus a mathematical archetype of the physical object which has yet to be materialised. The ability to manipulate a symbolic archetype leads to economy, convenience and speed in the earlier stages of a design. The accomplishment of the same results by varying the elements of a physical prototype would be slow, costly, often impossible. (In the later stages of a design the balance may change, and economy and speed may favour the testing and manipulation of physical models.)

The design concept for the product is then visualised as a system which is described in terms of a set of system variables, the design parameters. The mathematical archetype which has been set up determines the pattern of correspondence between the input and output variables of the system, that is, its performance. The next step is to determine the sensitivity of the performance of the system to variations in each of the design parameters, and to identify the critical design parameters as distinct from the less critical. At the same time a more quantitative idea is obtained about the expected overall performance of the system, and this may either increase or decrease confidence in the design concept being considered.

A system or complicated device can be thought of as an object which is itself a combination of objects of the next lower order of complexity. In the case of a complex system such objects would be referred to as subsystems. The subsystems may be combinations of components which in turn may be combinations of parts. A very complex system will usually have a hierarchical structure many layers deep. The design of the overall system requires an examination of at least the first order elements which compose it. At this stage of the preliminary design, further studies must be made to investigate the characteristics of subsystems and major components, and the tolerances required to ensure their mutual compatibility and proper fit into the system as a whole. While problems of compatibility are many and varied, it should be realised that those design parameters which are the least critical to the system can receive the major adjustments in accommodating the subsystems or components to enhance their mutual compatibility.

The next step is to analyse the stability of the proposed system and the extent to which it is affected by external or internal perturbations. The purpose of this is to make sure that the system as a whole is not inherently unstable, to determine whether any combinations of design parameters can lead to instability so that these may be avoided, and to evaluate the risks and consequences of environmental disturbances which might be sufficient to cause catastrophic failure.
For the design to advance further all major parameters must now be given specific design values. Of all the possible combinations of parameter values (that is, combinations which satisfy all the design constraints and could therefore be expected to work), there will be one superior to all the others, the optimum combination. The next step in the design project is to determine this optimum; methods for doing that are described in the next chapter.

Each of the earlier steps - sensitivity, analysis, compatibility analysis, stability analysis - has provided additional evidence in favour of or against the design concepts considered. The formal optimization step provides additional evidence for fixing the final design concept, and this is usually conclusive. Among all possible combinations of the design parameters a set has been selected which yields the best results according to the design criterion.

Since some time must elapse before a design project can be completed, and there will be other delays before the actual product will be used by the consumer, it is necessary at this stage to forecast future trends in the environment. This must be done in an attempt to determine conditions at the time the product comes into use, so as to ensure that it does not become obsolete in the meanwhile. Although the designer cannot commit his design beyond the current or immediately foreseeable state of the art, he must endeavour to accommodate the design to the impact of technological change in such a way as to secure adequate protection against obsolescence.

As well as considering the effects of future technical and social environments on the product, we have also to examine how the product itself will behave in the future by virtue of its own inherent characteristics. A product is designed with the goal of producing a certain set of desired outputs in a given range of environments for a given length of time. It is necessary therefore to predict its future behaviour with the object of ascertaining that as far as possible it will match its future environment. To prove the acceptable performance of a design concept recourse may be had to laboratory testing in which the physical environments that will bear on the product are reproduced. Time and space scales may be altered to suit the limitations of the laboratory. Testing to gain information on the performance of products tends to become increasingly common as more and more designs rely on innovation rather than evolution. It is also a powerful tool to aid paper and pencil design: it serves to verify design hypotheses, to generate new design information, to develop improvements of the design concept, and to expose difficulties which might have been overlooked in the paper design. Testing and experimental designing are usually more costly in time and money than paper design; therefore, they should be considered as augmenting and verifying the latter, when the technical needs and economic factors justify their use.

As a design progresses through these various steps, the original concept inevitably becomes more complicated. Before the preliminary design
is completed, it should be subject to a rigorous study to reveal any unnecessary complications and to discover every possible simplification. Good design has an aesthetic quality, the quality of simplicity.

The preliminary design phase begins with the decision to select the most promising design concept, this selection being confirmed or revised in the light of later information. Mathematical archetypes of the chosen concept are then set up and subjected to sensitivity, compatibility, and stability analyses. This is followed by optimization of the archetype, and then an attempt is made to predict how the product will measure up to future standards of excellence and how it will perform under the various conditions in which it may operate. The design concept may be tested in the laboratory and critical components subjected to special tests to prove their suitability, the results being used to revise the design concept if this is found necessary. Finally, every possible way of simplifying the design concept is studied before it is submitted as the proper solution for further development in the detailed design phase which follows.

As a result of the preliminary design, the overall concept of the product has been fixed, and its major components tentatively defined. This information is presented in a master layout drawing which may be changed in detail as the design of subsystems, components, and parts proceeds.

(3) Detailed Design.

As indicated in fig. (2.1) the detailed design carries the overall design concept through to a description of the final product. To do this the overall concept must be brought to a state of design that is clearly physically realizable. This state is achieved by constructing a prototype from a full set of design instructions, testing it, and revising both the prototype and the design instructions until the system or device is satisfactory for production, distribution, and consumption.

The steps in the detailed design phase are usually well understood and need only be outlined here. First, there is the preparatory work of setting a monetary budget for the project and a time schedule for its completion. Having decided to go ahead with a project, management must then mobilize and coordinate the technical manpower and resources to perform the design work and set up a project organization.

The second step is the overall design of the subsystems, and this follows the same general pattern as the preliminary design of the system — selection of design concept; analysis for sensitivity, compatibility, and stability; optimization. In this case care must be taken to ensure that optimization of a subsystem (or component or part) is consistent with optimization of the whole system or product. A provisional layout drawing is prepared for each subsystem which translates into drawings the results of the subsystem designs. These layouts become the basis for developing the design of the components.

The third step, the overall design of the components, then follows, this being practically a repetition of what has been described
for subsystems. As we move down to successive lower levels in the design, the objects we deal with become progressively less abstract and our concern with ultimate hardware becomes more immediate; in fact it may be possible to purchase directly some of the components. The results of the component designs are encompassed in provisional layout drawings which are the basis for detailed design of parts.

Parts are the elementary pieces from which components are assembled. Their detailed design requires a complete physical description; there can be no ambiguities about shape, size or material in the instructions for manufacture. The same kinds of questions about sensitivity are stability which arose in the higher levels of design are often important here, and for critical parts optimization is always important. The problems of compatibility and simplification have a special status in the design of parts. They lead to questions about tolerances in dimensions; mechanical, physical, and chemical properties and composition of materials; and quality of workmanship. Other problems of engineering design also become prominent. The part designer has close ties with the metallurgist, the production process engineer, and the tool designer. The choice of material for the part must be settled upon if this has not already been done; its heat treatment and surface treatment must be prescribed if they are to be applied. The producibility of the part must be considered, and, at least in a general way, the production processes established for its manufacture. The general means of production need to be decided since they reflect the manufacturing capabilities of the company and the tooling costs that will be incurred in preparing for production. Finally, the detailed drawings are carefully checked, this work being done by someone other than the original designer who is usually too emotionally involved in his work to see its faults. The detailed design of parts is followed by the compilation of assembly drawings for the components and systems. The prototype is then constructed and tested. Any difficulties in either of these operations and any shortcomings revealed in performance are analyzed, and where necessary, the design revised. A major concern is to restrict the effect of any changes, since small revisions may start a chain of consequences capable of destroying the integrity of the whole design.

Once again the iterative character of design work is apparent. After revisions have been made by redesigning, the construction of new prototypes and subsequent testing may follow, and these too may lead to further revisions. However, a successful project is highly convergent so that only a few iterations are required to reach a final solution.

2.2.2 The Design Process.

In the preceding section the vertical structure of engineering design was examined; this forms a skeleton around which a design project can be planned, organized, and evolved. Now in each of the steps in this structure, from the beginning of the feasibility study to the final revision of the detailed design, there is a typical sequence of operations which we
call the design process. This is essentially a process for solving problems in engineering design; it occurs at every stage of a design project, and imparts to engineering design a horizontal structure as well as the vertical previously discussed.

The design process consists in the gathering and organizing of information relevant to the problem situation facing the designer, who has then to create possible solutions, evaluate them, select the optimum, refine it, and communicate it to others. It also has an iterative character since often in its performance new information becomes available or new insights are gained which require the repetition of earlier operations. The design process resembles the general process or problem solving, but it uses sharper, and for the most part, more analytical tools which have been especially devised for engineering.

The design process is illustrated in diagrammatic form in fig. (2.2). The designer has first to analyze the problem in order to gain an understanding of it, discarding false and irrelevant data to make an unequivocal statement of the problem. This statement makes clear what goals are to be achieved, what difficulties must be overcome, what resources are available, what constraints will circumscribe any acceptable solution, and finally, what criteria should be used to judge the goodness of a possible solution. The designer has then to exercise his creative powers in order to create solutions to the problem, a solution being a synthesis of component elements which achieves the desired goal without exceeding the available resources or any of the constraints present. These component elements will be stored in the designer's memory or will be contained in the information that is given to him in his work. The types of information that he requires or that should be supplied to him are listed in fig. (2.2) and discussed in section (2.5) below. At this point we can note that the information required by a designer varies with the problem he is tackling. For example, knowledge of the engineering sciences is essential for designs with high innovational content, whereas with evolutionary designs the emphasis shifts to knowledge of engineering processes and costs as the competitive standing of the product then depends more on keeping costs of production down.

As many solutions as possible to the problem should be synthesized in the allotted time. These are then evaluated to find the most favourable solution which is then refined to give the optimum answer; if there is any doubt about its being satisfactory special tests may be carried out, and revisions made where necessary. The final solution is presented in a form in which it can be communicated to others.

2.2.3 Decisions in Engineering Design.

It is a characteristic of engineering design that when an attempt is made to solve a design problem, there is uncovered a substratum of sub-problems; the solution of the original problem is dependent on the solution of the subproblems. Thus suppose we begin with a primary problem Go
which has been analysed and a statement made of it in clear engineering terms. As illustrated in fig. (2.3), a number of plausible solutions are proposed, $A_1$, $A_2$, ..., $A_n$, only the first two being illustrated in the diagram. Each of the proposed solutions, when investigated for physical realizability, may give rise to a number of subproblems; $A_1$ may create $Q_{11}$ and $Q_{12}$, $A_2$ may create $Q_{21}$ and $Q_{22}$, and so on. If these subproblems are not clearly resolvable, solutions of them are investigated. This process continues, penetrating deeper and deeper into the hierarchical structure until a sufficient level of confidence is achieved to enable a decision to be taken.

Now during the course of a design project many decisions arise, some of which are critical as they have a major impact on the design. Decisions which are particularly critical as a class are those which arise after a design problem, occurring at any level in the design, has been studied and a number of possible solutions developed. Each solution may have various benefits or lead to various difficulties of implementation. Which solution to adopt is a critical decision for its answer affects the form and content of the design.

Suppose it is desired to make a selection from several competing design concepts, where each is believed with more or less confidence to have certain advantages and to be realizable within the budget allowed. To place the discussion on a quantitative basis, assume that it is possible to construct a weighting function to cover the set of advantages which are relevant to the decision. We can then measure the advantages to be gained from each design concept on some appropriate utility scale, and plot a point for each concept on a graph with the co-ordinate scales of utility and confidence, fig. (2.4). The outer points such as A, B and C form a convex set which dominate the inner points, and they alone therefore need be considered. If it turns out that one particular concept dominates all the others by having the highest utility and the highest level of confidence, then this would be the natural one to select. However, if several concepts appear in the convex set, a rule is needed for selecting among them. While there is no unique rule for discriminating between these alternatives it would be reasonable to choose that one giving the highest expectation of gain. We have then to consider the level of confidence we have in our judgments, the value assigned to each advantage, and the loss that would occur if the concept failed.

Let $Li =$ confidence level associated with the $i^{th}$ design concept in the convex set. 

$Vi =$ value assigned to its advantages.

$Si =$ loss experienced if the $i^{th}$ concept were selected and failed.

$Ei =$ expected gain by using the $i^{th}$ concept.

Then,

$$Ei = Li Vi - (1 - Li)Si \quad (2.1)$$

We then determine which concept makes $E$ a maximum, noting that the loss resulting from a failure is usually the same for all concepts.
For example, consider a case where there are three alternatives with

- \( L_1 = 0.98, \quad V_1 = 150 \)
- \( L_2 = 0.95, \quad V_2 = 200 \)
- \( L_3 = 0.90, \quad V_3 = 300 \)
- \( S_1 = S_2 = S_3 = 1000 \)

Then,

\[
E_1 = 0.98 \times 150 - 0.02 \times 1000 = 127 \\
E_2 = 0.95 \times 200 - 0.05 \times 1000 = 140 \\
E_3 = 0.90 \times 300 - 0.10 \times 1000 = 170
\]

and the third concept would be chosen.

However, if \( S_1 = S_2 = S_3 = 5000 \) then

\[
E_1 = 47 \\
E_2 = -60 \\
E_3 = -230
\]

and the first alternative is preferred. When the penalty for failure is small the level of confidence can be low; but when the penalty for failure is high the level of confidence must be correspondingly high in order to insure against catastrophic losses.

Engineering design proceeds by a continuous sequence of decisions. It has been the purpose of this section to point out that very often these decisions can only be made with a reasonable level of confidence by delving into the hierarchy of problem and subproblem. An attempt has been made to formulate a quantitative approach to the process of making critical decisions on the basis that the expected gain should be a maximum. It is realised, however, that there may be many situations in which the designer has to make subjective evaluations by relying on his own judgment or intuition rather than on an explicit mathematical process.

In the early phases of design the design concepts are far from physical realization and close estimates of costs are difficult. The critical decision of selecting one from a number of competing concepts of roughly equal advantage will be based on the levels of confidence associated with the competing concepts. The one chosen will reflect this emphasis on the level of confidence that it can be realized. In the later stages of design physical realization is easier to assess, only concepts with a high level of confidence in their physical realizability will be accepted; and when advantages are similar critical decisions will rest on the relative costs of producing the designs.

To recapitulate, decision-making in design has an iterative character, and often rests on investigations into substrata of problems. At all stages of design, decisions on the selection of design concepts are critical as they have a major influence on the form and content of the finished product.
2.3 PRODUCT PLANNING

2.3.1 Introduction

We now investigate the product planning function in an engineering company. Product planning will be defined as "the planning and co-ordination of the various processes which are essential for the conception, selection, and introduction of new products". It is the responsibility of product planning to initiate new design projects, and set the goal towards which the designer has to work.

In these days of expanding technology, those manufacturing enterprises are most likely to be successful which persistently and intelligently develop new and better products, and new and better ways of making and using old products. After all, a business like any other organism must either grow or adapt to survive. Business survival depends directly on profitable sales, which in turn depend on having the right products at the right time. Thus product planning is at the heart of business strategy. It affects, and is affected by, every activity of the business enterprise. Product planning must be based on a realistic evaluation of overall company objectives and company resources.

The planning of new products will depend on the size and type of company, the nature and use of its products. Some large companies have successfully concentrated on the manufacture of a single product, as for example in some high-output industries requiring large capital investments. At the other extreme there is the small company built up by one man around the manufacture of one product of which he has specialised knowledge. Furthermore, there are differences between capital goods and consumer goods. Manufacturers of consumer goods tend to have a wider variety of products and a shorter cycle of product change, chiefly because consumers are influenced by passing fashions in appearance and ornamentation. On the other hand buyers of capital goods are more interested in performance and economy, and producers of such equipment can therefore rely on fewer types and sizes. Another factor is the degree of competition, the more monopolistic an enterprise the less stimulus it has to plan new products.

This discussion will be based on the general case of a medium-sized company which wishes to expand by introducing new and better products. To achieve a satisfactory rate of growth the planned expansion of its range of products is a necessity, in fact its vitality will be reflected in the number of successful new products it brings onto the market. Planning for new products means planning for effective expansion and growth. However, there is evidence to show that only a minority of new products fully justify the expenditure of time and money required to bring them to the market. This underlines the need for careful selection of new products, and proper co-ordination of the people and departments involved in their development.
2.3.2 Programme for Product Planning.

Correct product planning leads to optimum application of company resources to achieve maximum profits through product leadership. While a company will suit its own peculiarities when establishing a product planning programme, its board of directors or top management must first carry out certain fundamental steps which are essential to effective product planning. The strengths and weaknesses of the company and its resources must be evaluated, as far as possible long-range objectives determined, and decisions made concerning the application of the company's resources to research and product innovation. The product planning function can then be organized and its policies decided. The detailed work of product planning begins with the creation of ideas for new products, and continues with the evaluation of these ideas and their progressive development to successful new products.

It is clear that a basic programme for product planning and development will proceed in the following stages.

1. Evaluation of company resources.
2. Determination of long-range objectives.
3. Organization of the product planning function.
4. Creation of new product ideas.
5. Evaluation of new product ideas.
6. Development of promising ideas into marketable products.
7. Analysis of the success or failure of each of the preceding stages.

Besides studying the selection and development of new products, product planning in its widest sense includes planning for any form of product differentiation. Methods of differentiating new products from existing products are:

1. Improvement of existing products.
   Improvement of (a) performance
   (b) appearance
   (c) quality
   (d) manufacturing techniques
   (e) packaging
   (f) marketing
   (g) servicing
   (h) name
   (i) price
   All of these improvements are aimed at increasing the utility of the product to the consumer.

2. Determination of new applications for existing products.
3. Expansion of present product lines, e.g., to give better coverage of performance.
4. Contraction of the number of models to eliminate unprofitable products.
5. Diversification into new product lines in (a) related fields
   (b) unrelated fields.
Each stage of the product planning programme will now be considered in turn.

(1) Evaluation of Company Resources.

This evaluation must cover human and physical resources as well as finances and markets. The various subjects to be examined are listed below.

(a) Human resources - the experience and capability of the following groups, their morale and personal attitudes.

(i) Board of directors
(ii) Managers
(iii) Engineers
(iv) Other specialists
(v) Supporting personnel
(vi) Labour - skilled, semi-skilled, and unskilled.

(b) Financial resources - capital structure, turnover, rate of earnings, contingent liabilities, bank balance, availability of new capital.

(c) Material resources - plant and facilities.

(i) Factories, stores, offices; their type, size, layout, condition.
(ii) Manufacturing equipment; type, size, condition, modernity, adaptability, over- or under-capacity.
(iii) Accessibility to transport, raw materials, markets, essential services.
(iv) Operating and maintenance costs.
(v) Ownership, leasing arrangements.

(d) Marketing.

(i) Total market for present product lines.
(ii) Fraction of total market for each product; reasons for not having a larger share of the market.
(iii) Price and discount policy.
(iv) Methods of distribution.
(v) Service and spare parts facilities.
(vi) Seasonal and other important cyclic factors.
(vii) Methods of advertising.
(viii) Market research ability.

The most difficult exercise here is the correct evaluation of the company's human resources. One can think of several examples of firms partly or wholly engaged in engineering but who have no directors with technical qualifications or training. Again, often an employee's value to a company is only recognized when he is on the point of leaving it or has resigned.

(2) Determination of long-range objectives.

Those in charge of a manufacturing enterprise must have a clear conception of its goals and the course they intend to chart for
its future operations. They must establish the overall objectives of the business and of its major functional departments. To do this involves the following activities.

(a) Business objectives: investigations into prospects and directions for the next ten years; in particular, forecasts of major economic, technological, and market trends, and formulation of general policy on expansion of operations by entering new fields.

(b) Financial objectives: decisions on the financial condition and structure of the company in view of the proposed product policy.

(c) Engineering objectives: determination of future requirements of technical manpower and facilities for research, design and development.

(d) Manufacturing objectives: decisions on the plant, facilities and manpower required for the company's future operations in relation to raw materials and markets.

(e) Marketing objectives: forecasts of future markets, their type and size, and the company's share of them; determination of policies on methods of distribution and service facilities.

At this stage company management has to decide what proportion of the resources available are to be allocated to the planning and development of new products. It is possible to classify the degrees of activity of a company in the field of product development, from merely staying in business to pure research:

(a) Barely staying in business by following competitors. This method of operation is obviously extremely dangerous to the company's continued existence.

(b) Improving the product continually to keep abreast of competition. This is the bare minimum a company can do with any real assurance of being able to stay in business.

(c) Improving and rounding the product line, with some products leading the field. This level of activity is probably the lowest a progressive company can attain.

(d) Expanding the range of products, but maintaining technical continuity based on company experience and talent.

(e) Diversifying products by entering new fields with no thread of technical continuity (possibly by company acquisition or merger).

(f) Undertaking exploratory research having no immediate useful application.

Probably most companies concentrate their efforts at a level corresponding to stage (d).

(3) Organization of the Product Planning Function.

The next stage is the organization of the product planning function with overall policies decided as a result of the preceding
investigations. Product planning is a complicated process with responsibilities which involve all major functions (engineering, manufacturing, marketing, finance) and which cut across the usual lines of authority. In very small businesses its successful execution and integration with company long-term policy may be the job of an individual or small group. In larger firms product planning can be carried out in a number of ways depending on the organization and the people in it. It should be the responsibility of a high-level staff group, functioning either as a special department or as a committee, and reporting to the chief executive. However, major product planning decisions should not then be taken without the advice and agreement of the functional managers.

To organize the planning of new products, either a special department or an interdepartmental committee should be set up within the company. Ways in which this has been done are set out below.

(a) Department.

(i) In some companies product planning is a separate department responsible to the general manager, or is part of a "business operation" department. This is the case in the Burroughs company in America where the organizational structure is as shown in fig. (2.5). Working on the same lines the Morphy-Richards company, an English domestic appliance manufacturer, created the position of product planner as a senior staff appointment.

(ii) In contrast to this approach, product planning may be arranged as a sub-function of one of the major functions. In companies manufacturing highly competitive products it is often part of the marketing function, while in companies manufacturing products of high engineering content, product planning is often part of Engineering, or Research and Development.

There are drawbacks in not having product planning reporting directly to top management, since it should reflect top management thinking and since its work cuts across most of the major company functions. If it is assigned to a sub-function the product planners tend to reflect the viewpoint of that functional department of which they are part, and it is more difficult to integrate product planning with overall company policy.

(b) Committee.

A large American manufacturer of kitchen appliances and furniture uses a product development committee. Its chairman is the manager of engineering and its members comprise senior representatives from management, engineering, manufacturing and marketing; it meets monthly. The Warner and Swasey company, manufacturer of machine tools and textile machinery, has a new product committee which meets as required and consists of representatives of engineering, marketing, and management. This company also employs an engineer whose full-time job is searching for new products.
These examples show that the formal organization of the product planning function can take various forms. Nevertheless in any particular company its objectives and responsibilities should be clearly understood, also the relationships of its personnel, their accountability and authority. As previously noted product planning can only be effective when policies have been formulated regarding

(a) improvement of products, expansion of product lines, their diversification or simplification.
(b) Technical development work (internal and sub-contract); to what extent is the company willing to invest in technical leadership?
(c) Acquisition of new companies, mergers.
(d) Manufacturing, the investment in new or special machines, the size of production runs, control of inventories.

Barometers should be set up to watch the progress of existing products - their profitability, share of the market, the number and cost of service calls, the ratio of orders received to quotations sent out. Ideally, new developments should be coming along before any of these controls shows a significant undesirable trend.


The product planning department or committee receives and evaluates ideas and submits proposals to management. These ideas may originate from departments within the company - engineering, marketing, product planning itself - or may be derived from outside. In his search for new ideas the product planner will make use of several sources for inspiration.

(a) Ideas from planned investigation of consumer needs aimed at finding gaps and opportunities in the existing market structure.
(b) Ideas as a by-product of normal company development, from engineers and others who think up new ideas in their day-to-day work in the design and development of the company's products.
(c) Ideas from planned technical research whose goal is the solving of specific technical problems arising out of attempts to meet a consumer need already established by market research.
(d) Ideas from "planned dreaming", that is from one or two people on the staff who are employed to spend their time dreaming up new product ideas.
(e) Ideas from random sources.
   (i) Unrecorded sources: fellow workers, friends, suppliers, customers, advertising agencies, in fact any person who may see the need for a new service or machine.
   (ii) Recorded sources: patents; licences from government departments or other companies; inventions; articles in professional and trade journals, lists of available products, lists of imported products.
Product planners must be aware of all the sources of new ideas available to them, and ensure that as far as possible these sources are stimulated and used properly.

Product planning depends on a clear understanding of the effective needs in the community which are to be satisfied by the creation of new products. The key word here is "effective" as we must avoid the hazard of assigning to consumers the needs we feel they ought to have, because we are likely to be biased by our own opinions of what is technically possible. Moreover, consumers themselves may not be reliable guides to effective needs, what they say they want may be surprisingly different from what they will buy later when the product becomes available. This problem is a very real one for company management since errors in judging effective needs will usually cause a much greater financial loss than failure to produce a workable design.


Once ideas for new products have been generated they have to be evaluated in order to sort out those which show most promise of leading to a marketable commodity. Each product idea has to be analyzed as a complete project operation with implications for all of the company's major activities, design, development, manufacturing, marketing and finance. During this analysis many questions will be asked: What resources will be required? How long will it take to develop the new product? Will consumer's needs change in this time? What will competitors offer? What will be the economic climate? What will be the effect of the new product on the company's existing products?

There are three important criteria to be applied to the evaluation of ideas for new products. First, the return on the capital employed; this needs no comment. Secondly, the size of the project's contribution to the business; if the project will form only one percent. of annual turnover, say, then its contribution to the company's profits will still be small, even if the return on capital is quite high. Thirdly, the extent to which the project will help in achieving the company's overall strategy and objectives; a project may be undertaken simply as a form of insurance for staying in business, or perhaps to establish the company's name in a new market, or for some similar reason.

In order to complete the statement of the problem to be given to the designer when he commences the design of a new product, an analysis should be made of the boundaries and boundary conditions which will apply to the new product. This analysis is illustrated in general form in fig. (2.6); it proceeds in the following steps.

(a) The desired outputs of the products are derived from the effective needs of the consumer. The outputs should be expressed in more precise language than the needs, and should reflect what the product does or provides in response to these needs.
(b) The undesired outputs of the product are deduced. It seems almost inevitable that undesired outputs accompany the production of those desired. A refrigerator extracts heat to keep food fresh; simultaneously it extracts moisture which spoils the flavour. A lamp produces light for reading, but at the same time the heat it radiates makes us uncomfortable.

(c) The inputs, which the product will transform into outputs, are deduced. For example, if the product delivers mechanical energy we know that fuel or energy must be an input. The inputs can be classified into five categories:

(i) physical - energy, materials, motion;
(ii) human - effort, control, or mere presence;
(iii) informational - error signals, coded data, instrumental controls;
(iv) economic - costs of operation, maintenance and depreciation;
(v) environmental - heat, shock, moisture, etc.

(d) The constraints which will apply to both inputs and outputs are determined. These will usually take the form of specifications, limits, tolerances, and other definitions of acceptable or limiting qualities. All outputs, desired or undesired, all inputs, purposeful or incidental, should be considered, and if possible, proper bounds set for them in order that the product be compatible with its purpose, its environment, and the consequences of its use.

(e) The constraints on the product itself are considered along with any design parameters that are now evident. The constraints may be on size or weight or speed or other attributes of the product. Many of the attributes so constrained will be design parameters.

(f) Appropriate measures of value for the outputs and inputs and for the design parameters are set out. By doing so, we are able to express the analysis in quantitative terms. In many cases the assignment of measures of value will be obvious, as in using feet to measure the dimensions of a product, but in other cases it will require great ingenuity, and in still others it will remain intangible. For example, it is very difficult to assign a proper meaningful measure of value to safety, although sometimes this can be done.

(g) The criteria for measuring the goodness of proposed designs are developed from appropriate relationships among the variables, namely the inputs, outputs, and design parameters. Some of the more useful criteria will be expressed quantitatively. In general, a criterion expresses the amount of the output functions that can be realized from various amounts of input resources.

To sum up, it is essential to make well-planned analyses of effective consumer needs and the ways in which it is proposed to satisfy these needs. As evaluation proceeds the criteria of economic worthwhileness and importance to company objectives are applied in order to arrive at those ideas which show most promise for development into new products.
(6) Development of Promising Ideas.

The progressive development of promising new ideas should be carried out systematically in well-defined stages, so that the project as a whole is subject to efficient control by making an assessment at the end of each stage and re-checking that it has achieved its purpose before the next stage is begun. It is not proposed to discuss the development procedure in detail as this depends very much on the product under consideration. However, in a typical case controls over the project would be maintained at these stages:

(a) estimation of costs of development;
(b) determination of performance specifications;
(c) design of prototype;
(d) manufacture of prototype;
(e) testing of prototype.

Finally, the product is ready for the market.

(7) Follow-up Analysis.

By analysing the sales and profitability of the new product after it has been placed on the market, company management assesses its success or failure, and the success or failure of each of the preceding stages. If any deficiencies are revealed action must be taken to improve the product planning and development programme.

2.3.3 Conclusion.

Most firms recognize new product development as the key to their survival. The exploration of possible new products must be a continuing process, for, as is well known, only a fraction of the ideas which at first seem good, blossom into commercial success. The cost of separating the successes from the failures may be large, often unnecessarily so, because the project is not abandoned until the product is ready for production, or perhaps has even been unsuccessfully launched on the market. Effective product planning is the means of saving much wasted effort and disappointment in industry.
2.4. CREATIVITY IN ENGINEERING DESIGN

2.4.1. Introduction

Creative effort is a distinctive feature of engineering design. At each stage of design, the designer has to synthesise solutions to the problems he encounters. In the discussion which follows our aim will be to arrive at a working understanding of human creative ability and how it affects engineering, without entering into a deep philosophical and psychological study of a difficult and profound subject.

The need for creative achievement is now well recognised. History shows us numerous examples of civilizations which have risen to power in periods of physical and intellectual growth, only to decline as the people became so enamoured of their own superiority, so impressed with their past achievements that they lost interest in working for further change.

The opportunity for solving problems is always with us. Only the local environment and the divine discontent of individuals determine whether or not problems will be sought after and solved. In the past it has often required a fortunate combination of stimulating leadership, intense motivation born of bondage or slavery, and other powerful stimuli to overcome the effects of environment. Our nation is not immune to this ageless cycle of rise and fall, nor are our industries, nor are we ourselves. Through over-indulgence in pleasures and concern with trivialities, we can start to decline without noticing it. On the other hand by applying the antidote - directed creativeness - we may climb to new heights of achievement. We have to meet the challenge and learn to apply creativeness profitably to our own professional work as engineers.

In general we have to decide how we will respond to the situations in which we work. At the lowest level we can remain blissfully ignorant of what our situation calls for, and work today and tomorrow just as we did yesterday and the day before. At the next level our conscience tells us that some new action is necessary but lethargy prevents us from doing anything; we hope that our inaction may slip by unnoticed, and that the situation will somehow solve itself. If sufficiently motivated, we may resolve the situation as best we can according to well-established practices or routines, and achieve, or attempt to achieve, some solution through the application of known skills. However, if highly motivated, either through fear of failure after being placed in a new and unfamiliar situation, or through a personal decision to go beyond the application of known skills in achieving a solution, we find ourselves in a perplexing situation, we have a problem to solve, a solution to create.

A solution can be regarded as an area in which we may expend our mental and physical energies. Thinking is a frustrating mental activity, and we may think for long periods without any seemingly tangible results. Most people, therefore, reduce their situations to a mere
physical expenditure of energy as quickly as possible and become situation-resolvers rather than problem-solvers. Common examples of dodges for resolving situations are: passing the buck, reverting to a committee, arranging to be out of town until the crisis is past, and drinking.

2.4.2. What is Creativity?

To help clarify ideas on creativity, consider the examples of two famous engineers, James Watt and Sir Frank Whittle.

As is well known, James Watt invented the condenser for the Newcomen steam engine, and thus opened the way for the general application of steam power. Watt became interested in improving the engine when he discovered, while repairing a model at the University of Glasgow, that its method of operation was extremely inefficient.

In the Newcomen engine power for each stroke was developed by first filling the cylinder with steam and then cooling it with a jet of water; this cooling action condensed the steam and formed a vacuum behind the piston, which was then forced to move by the pressure of the atmosphere. Thus with every stroke the cylinder was alternately heated and cooled, and calculation showed Watt that this process was extremely wasteful of the heat supplied to the engine. Therefore, if he could prevent this loss of heat, he could reduce the engine's fuel consumption by more than 50%, and accomplishment that was obviously worthwhile. Watt worked over this problem for two years but could find no solution to it. Then on a fine Sunday afternoon he went for a walk, and in his own words, this is what happened.

"I had entered the green and passed the old washing house. I was thinking of the engine at the time. I had gone as far as the nerd's house when the idea came into my mind that as steam was an elastic body it would rush into a vacuum, and if a connection were made between the cylinder and an exhausting vessel the steam would rush into this vessel and might then be condensed without cooling the cylinder... I had not walked further than the golf house when the whole thing was arranged in my mind."

Watt had then conceived his condensing steam engine and laid the way for later developments of this type of prime mover during the period of the industrial revolution in England. The essential points in his experience from the standpoint of creative thinking are as follows. Watt had set up for himself a problem which, after two years of work and intensive thought he had failed to solve. One day, while indulging in a reverie during the enforced idleness of a Scottish sabbath, the solution of the problem came to him, unexpectedly and without effort.

Sir Frank Whittle was born in 1907 and entered the R.A.F. as a youth of sixteen. In the years 1926 - 28 he was a flight cadet at the R.A.F. Station, Cranwell. Towards the end of the cadet training course, he had to write a thesis and chose for his subject, "Future Developments
in Aircraft Design". At this time Whittle began thinking in terms of speeds of 500 m.p.h. when the top speed of R.A.F. fighters was 150 m.p.h. It seemed to him unlikely that the conventional piston engine and propeller combination would meet the power plant requirements of the high-speed, high-altitude craft he had in mind; and in his thesis he discussed the possibilities of rocket propulsion and of gas turbines driving propellers. It did not occur to him then to use the gas turbine for jet propulsion.

During the eighteen months after he left Cranwell Whittle continued to consider this problem in his spare time from his flying duties — the quest for a suitable power plant for a very high-altitude, high-speed aeroplane. He gave much thought to a jet propulsion arrangement in which the propelling jet was generated by a low-pressure fan driven by a conventional piston engine, both the fan and its driving engine being situated within a hollow nacelle or fuselage. His ideas included provision for extra heating of the air compressed by the fan by the burning of additional fuel before expulsion from the propelling nozzle. However, he eventually came to the conclusion that this offered no real advantage over the piston engine-propeller combination.

Towards the end of 1929 while he was attached to the Central Flying School at Wittering, the idea suddenly occurred to Whittle of substituting a turbine for a piston engine in this arrangement. He had returned to the idea of a gas turbine but this time of a type which produced a propelling jet instead of driving a propeller. Once this idea had taken shape it seemed odd to him that he had taken so long to arrive at a concept which seemed very obvious and of extraordinary simplicity. He patented his idea after it had been turned down by the Air Ministry in January, 1930.

In these two examples, the engineers were faced with difficult conceptual challenges where they were not readily able to find the desired solutions. Of course, they were sufficiently well acquainted with their work to have already stored in their memories the bits of knowledge necessary for the final insight to occur. In each of these cases the individual's creative effort took place in three well-defined stages, often called saturation, incubation, and illumination. The same characteristic steps have been observed in many other instances which space precludes mentioning here. First, there is an intensive attack on the problem in which the worker saturates himself in all aspects of it without achieving satisfaction. In the second stage the worker's interests become absorbed elsewhere and the problem ceases to occupy his conscious mind. Then, in some chance moment of reflection his mind once more drifts back to the problem and an illuminating flash is received which leads to the solution.

"Creation" and "creativity" are very difficult to define precisely. The definition of a "creation" adopted here is: "a new and useful association of existing elements." It is interesting to note how Whittle's invention accords with this definition. He created a new aircraft power plant by the combination of two existing elements, the gas turbine and propulsion by the reaction of propelling jets. We have noted how he had
previously thought of using a piston engine with a form of jet propulsion but had rejected this combination because it was impractical, and thus did not satisfy the criterion of usefulness included in the definition. In professional work our creative activities must be directed so that the results are of value to others; the worth of creative work depends greatly on the objective chosen. In other words the new combination of elements must have some definite purpose. Creation consists in avoiding useless combinations and in choosing those that are useful. Discernment and selection are essential features of this process.

If the existing elements are unrelated a high order of creativity may be required, for example in combining the notes of a musical scale. In general, the more closely the elements are related or constrained the lower the order of creativity.

2.4.3. Creative Thinking.

With the aid of a dictionary, definitions can be given of the mental processes most relevant to this discussion.

Thinking: the exercise of our powers of judgment, conception or inference; reflection for the purpose of reaching conclusions.

People think only when exercising their mental powers to some purpose, towards some goal. To create deliberate, worthwhile change inherently demands much thought, and we cannot begin too early in life to cultivate this mental discipline.

Inference: the deriving as a consequence, conclusion or probability; the necessary consequence of a chain of reasoning.

Inference is the mental power that finds its expression in logic and the deductive sciences.

Conception: the power of the mind to form ideas.

Judgment: the operation of the mind, involving comparison and discrimination, by which knowledge of values and relations is mentally formulated.

The use of one's powers of conception and judgment is clearly vital in creative work. The question arises, is the formal educational pattern too closely directed and disciplined so that these powers are neglected and die? Do the majority of mankind, except in their inquisitive childhood days, live largely by impulse and custom, asking few questions because they suppose they are already in possession of all the essential answers? From his own experience of formal education Albert Einstein once wrote, "It is nothing short of a miracle that the modern methods of instruction have not yet entirely strangled the holy curiosity of enquiry; for this delicate little plant, aside from stimulation, stands mainly in need of freedom; without this it goes to wreck and ruin without fail." On another occasion he pointed out that imagination was more important than knowledge. Furthermore, as we grow up the urge to conform to the group in which we live inhibits the development of our power of judgment. It appears that this power, the ability to discriminate, to secure and weigh alternatives, is normally less well-developed than our power of logic.
To help our understanding we can construct a crude picture of how our minds operate, see fig. (2.7). The memory is a vast storehouse containing every experience and bit of knowledge or sensation that we have ever encountered. The knowledge that we use frequently or to which we ascribe special importance is located in the front of this storehouse. Each bit of this knowledge is pigeon-holed away, ready to slide out to consciousness upon request. All the other information is stored rather haphazardly, and can be difficult to ferret out.

The opening of the memory to consciousness is covered by a filter that is moved about by judgment, reflex, or some other facility. To understand the function of this filter, let us recall that in tuning a radio, for example, we turn a knob that adjusts an electrical filter so that it will pass only one desired signal to the speaker. At the same time, it will suppress reception of the other hundreds of radio signals that are simultaneously present in the air. We can look upon our judgment as establishing a similar filter whenever we think. In the normal unthinking condition any external demand merely sets up an appropriate reflex filter, as fixed and limited in reception as the one-signal taxi fleet radio. This filter calls for and receives the habitual response from the storehouse. When a sufficient emotional drive is present, however, our judgment takes over control of this filter and sets up certain demands on our imagination.

Our imagination is the active searcher for, and combiner of, any pertinent bits of knowledge either in the storehouse or being gathered by the senses. It will freely combine any elements of information from these sources and offer them to the filter. The combined information that fits the current requirement of judgment passes through the filter for inspection by our consciousness. The combinations not satisfying the filter fall back into the storehouse and are lost. An unusual drive must be present before any person will attempt actively or consciously to direct his "filter" for pronounced creative accomplishment. Many creations, for instance, have been accomplished in moments of stress, during wartime or when the creation was necessary for survival. Also many scientific advances have been made because the scientist simply would not let nature continue to pull the wool over his eyes.

2.4·4. Barriers to Creativity.

Lack of creative problem-solving by engineers is not so much due to the absence of creative potential as it is to the various blocks and barriers to creativity. Once these barriers have been identified and a conscious effort made to remove them there is an immediate upsurge of creative output. The engineer should develop the habit of creating so that he can apply his creative ability to a wide variety of technical problems. The major barriers to creative thinking are now discussed.
(1) Habit.

Habits are useful servants that allow us to perform automatically many daily tasks without expending any mental energy. Habits are treacherous. Unless we are careful, more and more of what we do becomes a habit until we spend days, even weeks, scarcely having to think at all. We must be ready to identify and appraise the value of our habits both to ourselves and to others, and to discard them if necessary. Otherwise they will build a thick wall of complacency and pride about the way we are now doing things, until they have completely smothered our will.

A very common obstacle to creative problem-solving is the carry-over of past conditioning of thoughts and actions to new problems. Where this happens, engineers attack new problems only with the methods and approaches that have proved successful before. An engineer can become aware of his tendency to habit-transfer if he occasionally asks himself questions such as: "Have I relied solely on past experience? If so, was it because of a considered decision that this was the best approach, or was it to avoid the effort and worry that a new approach might entail?"

(2) Fixations.

Psychologists have identified an attribute which they call "functional fixedness". Once we ascribe a function to a given object we seem unable to think of using it for some other function; the use of an article one way or for one purpose blinds us to its other possible applications. This results in a narrowing tendency to remain within the obvious boundaries of a problem.

(3) Perceptual Barriers.

Perceptual barriers obstruct acquisition of true, adequate, and relevant information. They may take a number of different forms.

(a) Difficulty in isolating the problem, in separating the real problem from related problems.
(b) Difficulty due to narrowing the problem too much, paying little or no attention to its environment.
(c) Failure to distinguish between relevant and irrelevant or false data.
(d) Difficulty in seeing remote relationships.
(e) Failure to distinguish between cause and effect.

Of course the problem must be stated clearly and concisely in the first place, with no extraneous matter, and in such a way that the solution is not included in the statement. An example will help to clarify this. Suppose the problem is to design a better toaster, then a narrow statement of the problem would lead only to consideration of devices which use radiant electrical heat. If the problem is posed broadly as the dehydration and browning of the surface of bread, then other approaches are more readily seen to be possible, e.g., chemical, electronic, as well as other radiant heating methods.
(4) Goals.

Over-organization and insistence on meeting distant goals can inhibit creative work. Because the final product of the creative process is not known in advance it is inherently impossible to specify close deadlines and narrowly defined goals. It has been said that goals and time limits are for creation what adrenalin is for the heart, the right amount stimulates but too much causes failure. Goals should be presented as opportunities or challenges, but only rarely as obligations.

The setting of goals and the preparation of plans for their achievement can be difficult and time-consuming. On the whole, though, it is a necessary activity in order to ensure the most efficient procedure for creative work, with minimum time and energy expended on side issues. By planning definite goals we ensure the highest probability of success. This is in sharp contrast to industrial history where chance has played such a tremendous part. But in an intensely competitive economy business can no longer afford to wait for chance impulses to provide its forward steps. It can ill afford to wait until budget time each year to start looking for some ideas to be explored the following year.

Each individual too, if he wishes to maximise his contribution, must make the best marriage of his aptitudes and experience with the needs of his particular situation and propose creative work accordingly. In the preparation of such proposals he will naturally formulate a desirable goal and a specific plan for its accomplishment. This plan should have a final deadline and contain a number of intermediate, subsidiary deadlines so that a reasonably high rate of interest is sustained throughout. Properly used, planning and scheduling are the servants of the creative worker, not his master.

(5) Emotional Barriers.

Often an engineer's work is adversely affected by emotional barriers which can act as very powerful restraints. Two such barriers are the fear of making mistakes and the fear of censure by one's colleagues. Unfortunately, these fears represent states of mind which are more common than they should be; they have a malign influence in engineering as in other fields of human endeavour.

(6) Environment.

The wrong environment can stifle a would-be creator. Examples are: supervisors who measure results in terms of jobs completed and do not allow time for the hard thinking creative effort demands; fellow-workers unreceptive to new ideas and who demand conformity with the old ways; the presence of noises and other disturbances which interrupt trains of thought.

The right environment provides a receptive atmosphere loaded with ideas. The arrangement of these ideas in a new combination must occur first in the mind of an individual, but the availability of these ideas around him greatly increases the likelihood of this occurring. This is, of course, one of the classic arguments in favour of a free
democratic society in preference to a totalitarian regime. In a free society the creation and exchange of new ideas is widely practised and admired, whereas in a totalitarian state the flow of ideas is restricted to those which meet the approval of the men in power. Dr. J. Bronowski has written, "Not all societies are interested in creativity. Insects, for example, stopped evolving a long time ago (ants nearly five million years ago). They are satisfied with what they are, see no reason for change. They discourage originality or creativity by eliminating innovations. Among men, only two societies have been truly creative - Athens from the sixth to the fourth century B.C., and Europe after the Renaissance. Sparta was too moral, Egypt too religious, China too contemplative. . . . Society must be stable, but interested in change (hence not static), must be more concerned with what you produce than the way you live, must be impressed by action and future, not contemplation and life after death."

2.4.5. Creative Engineering.

The most important barriers to creative effort have now been discussed. Once these are recognized the way is open for the engineer to take constructive action to remove them. In many cases, the path to a good idea can be long; often it is accomplished only after many inadequate ideas have been generated and considered. The study of the poor ideas lays the basis in understanding without which the good idea could not be achieved. Creative workers have evolved techniques to help themselves overcome their habits and stiff attitudes. A creative technique is anything that can give or lead to a fresh point of view. Some creative techniques are as follows.

(1) Experience lists - lists of ideas and problems successfully overcome in the past.

(2) Check lists - lists of questions for the designer to ask himself to help generate new ideas. An example is given of a widely used check list.

Put to other uses? New ways to use as is? Other uses if modified? Adapt? What else is like this? What other idea does this suggest? Does past offer parallel? What could I copy? When could I emulate?

Modify? New twist? Change meaning, colour, motion, sound, odour, form, shape? Other changes?

Magnify? What to add? More time? Greater frequency?


Understate?

Substitute? Who else instead? What else instead? Other ingredient? Other material? Other process? Other power?

Other place? Other approach?
Re-arrange? Interchange components? Other pattern?
Other layout? Other sequence? Transpose cause and effect?
Combine? How about a blend, an alloy? Combine units?
Combine purposes? Combine ideas?

(3) Explanation of difficulties. If a person takes his problem to a colleague and explains its difficulties, his own mind is often stimulated to look at the problem in a fresh light.

(4) Brainstorming. This is a well-known group technique in which a group sets out deliberately to think up as many ideas as possible for the solution of a given problem.

(5) "Gordon" technique. This is also a group technique originated by a Mr. J. J. Gordon, who asks his group to discuss some work of general significance, such as "structure" or "separation", in the hope that new ideas or applications will emerge.

The ideas generated by these methods have subsequently to be appraised and evaluated.

Consider now the important qualities possessed by the creative engineer. These will include:

(1) Intellectual integrity.
(2) Persistence, the capacity for painstaking, arduous work, and obstinate persistence in the face of difficulties and frustrations. Michael Faraday said that the creative thinker "should be a man willing to listen to every suggestion but determined to judge for himself. He should not be biased by appearances, have no favourite hypothesis, be of no school, and in doctrine have no master. Truth should be his primary object. If to these qualities be added industry, he may indeed hope to walk within the veil of the temple of nature."
(3) Driving curiosity. This keeps the mind delving into the why, how and what of old and new devices and phenomena encountered.
(4) Constructive discontent. This is a refusal to lapse into passive acceptance of the status quo; it is manifested by a questioning attitude and a continual search for new and better ways of accomplishing desired results.
(5) Self-confidence and willingness to take risks. These qualities give the creative person courage to transcend accepted patterns of thinking and to stick to convictions in the face of discouragement, disapproval or censure. The fear of making mistakes can be a devastating emotional block to creative activity.
(6) Power of concentration, the ability to suppress diverting thoughts, to become totally involved in the problem.
(7) Openness to experience, lack of rigid boundaries in concepts, tolerance of ambiguity where ambiguity exists.
Earley in this discussion two important inventions by James Watt and Sir Frank Whittle were mentioned; these famous men possessed most of the qualities listed above in abundance. Whittle, for example, in his first jet engine designs proposed to obtain much higher pressure ratios across his compressor and turbine at much higher efficiencies than contemporary practice thought possible. The rate of heat release in the combustion system of his engine was many times greater than values previously used. Not only did he have the genius to conceive the idea of the turbojet engine but also the drive, persistence, and willingness to take calculated risks to carry the project through to the goal of manned flight in the face of tremendous difficulties.

Training programmes have been devised to develop personal creative skills, and have been instituted in many of the larger American engineering companies, such as United States Steel, General Electric, and General Motors. A typical one consists of twelve sessions, each one and a half to two hours, covering these topics, most of which have been mentioned in this discussion.

(1) Reasons for a training programme in creativity.
(2) Definition of creativity.
(3) Importance of ideas and imagination.
(4) Contrast of judicial and creative thinking.
(5) Discussion of non-creative mental processes.
(6) Discussion of "laws" of association.
(7) Description of the characteristics of creative people.
(8) Ways in which everyone uses creative ability.
(9) Effects of past experience and formal education on creativity.
(10) Examination of scientific hunches.
(11) Discussion of barriers to creativity.
(12) Organized approach to problem-solving.

To sum up, creative effort is of vital importance to engineering design, as in fact it is to all human activities. This investigation into the subject has been aimed at enlarging our appreciation and understanding of its difficulties. Many common barriers to creativity have been discussed, and ways pointed out for identifying them and removing them. While the designer's inherent creative powers cannot be altered, he must learn to use the ability he possesses as effectively as possible.
2.5. Communications in Engineering Design

2.5.1. Input of Information to the Designer.

Throughout his professional life the engineer has to solve problems. Problem solution requires information, whether that information is acquired directly through personal experience, or indirectly from communication with other people or from written records. Man has to enlist the collective power of his fellows in solving the environmental problems facing his group.

Design is essentially a process of gathering, organizing, and combining information, and the design engineer requires an efficient supply of information in order that he may do his job properly. This implies some form of Technical Information Service, which in a large organization may be made a separate department. Even in a small engineering firm there should be one man whose full-time duty is to keep abreast of research and new developments and present the results to the design department. Of course, the gathering and processing of information for the designer has a cost which must be balanced by the worth of the evidence bearing on the success or failure of a project. It is the responsibility of engineering management to strike this balance.

It was pointed out in section (2.2.2.) that the design engineer requires information on some or all of the following subjects:

1. Engineering sciences
2. Engineering materials
3. Engineering processes
4. Engineering costs
5. Special components
6. Company policy - planned production rate, variety control, standards
7. Previous designs
8. Competitors' products.

These categories are largely self-explanatory. With regard to item (1) the designer must be careful not to overlook any engineering sciences which are relevant to his work, for example, not to overlook the human sciences if the product is to be used in an environment containing people. Item (5) covers special components which would probably be obtained from outside suppliers, bearings, seals, and fasteners, for instance.

In a particular case the designer should analyze his project to determine exactly what type of data he needs and in which categories he is most interested. In the author's experience, engineering firms are very haphazard in their supply of information to the designer who must therefore exercise his own initiative. It frequently happens that designers are left in the dark as to the nature and quality of a competitor's products, information that is available to the company's marketing department but which is not given to the design department because of lack of awareness
of its importance. Design work is often hampered quite unnecessarily by failure to identify and collect all the information relevant to a project.

Apart from a lack of appreciation of its value, there are two important causes of inefficiency in the supply of information to the designer: poor communication techniques, and poor records. These lead to waste of time and effort as the searcher is unable to find useful information in a reasonable time. Moreover, as the amount of literature published doubles every ten to fifteen years, the sheer volume of documents makes it difficult for the unaided engineer to make effective use of technical literature. This situation is deteriorating, and to overcome it professional engineers must have an efficient library service able to identify and locate pertinent information on specific subjects by literature surveys, bibliographies, reading lists, and so on. Also, a great deal of time is spent by some designers in reconnoitring, searching, and trying to find parts which have been used before, so as to avoid the needless creation of a new part or tool, or the procurement of a new material. One of the main reasons for excessive variety is the absence of an accurate means of identification and location of past designs. The first essentials in information retrieval of this kind are well-defined codes, grouping similar items according to their common features and sub-dividing them by their differences. In all engineering work it is necessary to identify, classify and code past efforts to produce a memory bank for future use.

As a basis for organizing technical information one should first distinguish between (1) news, (2) data and (3) background. News refers to information on new ideas, activities, products; data refers to answers to specific questions; background refers to the state of the art of a particular topic.

(1) News.

Much technical reading is done to keep up with the latest developments, and the primary source of technical news is the specialist periodical. Many designers have a general interest in a number of fields, and at the same time are concerned in detail with several special techniques or studies. The number of relevant periodicals may then be inconveniently large, while none may offer all the detailed coverage required. The only way for a busy man to scan dozens of periodicals is to have himself provided with a list of the titles of all the articles which have appeared recently. This may be compiled weekly in the library of his organization or in a public reference library. It can be scanned in a few minutes and need not be compiled by the engineer himself; the engineer can select items from the list, and there will then be a reasonable chance that most of his reading will be purposeful and useful.

The effort required to prepare scanning lists from the many sources available (including abstracts, reviews, and digests) is proportionately smaller when it can be done by a specialist serving a number of engineers. The scanner may have this as only part of his job, at the one extreme, or may be a member of the staff of an Information Department at
the other. Specialisation is desirable because it ensures that the scanning is done regularly, and because it covers a far wider selection of the literature than the engineer can hope to cover on his own. The use of a weekly scanning list also reduces the numbers of periodicals that must be bought and avoids the delays arising from the circulation of periodicals to long lists of people.

(2) Data.

In order to get a useful answer it is necessary to put the correct question. The best method of obtaining data accurately and quickly is a verbal discussion with an expert who can make sure he is giving the type of answer required. The designer should keep a list of such expert sources available by his telephone. For enquiries where answers would be expected to appear in some standard work of reference, the first approach would naturally be to the nearest library. However, it should be noted that series of excellent data sheets and booklets on subjects of interest to the designer are published by magazines such as "Engineering Materials and Design", "Machine Design", "Machinery", "Product Engineering". Where complex or unusual data are required, it is necessary to turn to lists of titles of papers and specialist publications; annual or cumulative indexes should be consulted. Data often have to be manipulated to bring them into the form required for use, and the demand for a particular item is always likely to be repeated later. It is therefore desirable that information arising from such enquiries should be retained and organized to avoid subsequent duplication of effort.

(3) Background.

The collecting of literature to provide background to some topic is not generally as urgent as data enquiries often are, but will be more frequently required to be as complete as possible. If the enquiry is not undertaken by the enquirer himself, it is important that the searcher be well-briefed so that a minimum of time is spent in selecting irrelevant material.

The sources of information to which the designer refers are as follows.

(1) Books.
(2) Magazines, periodicals.
(3) Proceedings of learned societies.
(4) Reports, particularly of government, university or private research.
(5) Patents.
(6) Manufacturer's catalogues.
(7) Directories - trade, technical, etc.
(8) Standards - SAA, RSS, ASA, ASTM, API, etc.
(9) Codes and regulations - government and semi-government.
(10) Personal communications.
The commonest method of organizing technical information from these sources is to set up an engineering library. This acts as a clearing house for all kinds of literature and provides a central source of books, periodicals and pamphlets, thus preventing wasteful duplication. A library contains organized literature of widely varying content and physical form, and makes available special reference services.

A large company may set up a Technical Information Department as part of its engineering organization. The aims of such a department are to minimize loss of productive engineering time spent in routine information studies and to prevent the duplication of the work of others in engineering problems. Its services include:

1. Product searches, literature searches, bibliographies.
2. Collection and distribution of technical information on new materials, processes, products.
3. Distribution of information on pertinent technical papers, articles, and reports.
4. Maintenance of library with indexes and filing systems.

In design departments it is common practice to assemble information frequently used by designers into a booklet or drafting manual. Properly organized and concisely written, a drafting manual is an enormous aid in the preparation of engineering drawings. It is a source of standard and recommended procedures and practices which are to be followed in order that the intentions of the designer are correctly transmitted to and understood by manufacturing and other departments. It also gives standard design data and realistic manufacturing tolerances which help keep fabrication costs down. While such a manual takes much effort to prepare, the advantages gained are worthwhile. As a source document, the drafting manual must record the decisions and agreements reached between engineering and manufacturing. Items such as drafting procedure and practice, standard designs and attainable tolerances are of value only when understood and used.

Over and above the collection and distribution of information for a particular design group, the question arises as to whether there should not be design information centres serving the nation. The task of maintaining the store of information in useful fashion is tremendous. The gathering, storing, up-dating, and retrieving of such data is so large an undertaking and of such importance that in the United States of America it has been proposed that a few immense design-data-processing centres be established at strategic locations. These centres would then be available to designers throughout the country, information on a particular topic being obtained by presentation of properly coded queries to the computers.

2.5.2. Output of Information from the Designer.

The completed design has to be communicated to those responsible for its manufacture, and should be expressed in a form which contains all necessary information, clear and unambiguous. This information may be
transmitted by various methods of which the following are the most important.

(1) Drawings
   (a) detail drawings of parts
   (b) assembly and sub-assembly drawings
   (c) sectional and general arrangement drawings.

(2) Parts lists
(3) Written specification and instructions
(4) Models.

In practice there is considerable variation among different firms in the level of precision with which this information is conveyed by recorded means. Some firms rely to a large extent on verbal communication or on an implicit understanding of the designer's requirements based on previous experience. Here the tacit assumption is made that the cost of obtaining more precise information from the designer is not economically worthwhile, that, for example, he need not specify all tolerances on detail drawings as his intentions will be understood sufficiently well by the production department. Since proper communication between design and manufacturing is essential to the successful evolution of the product and to the maintenance of adequate records, it is always preferable that this communication be made in writing rather than by unrecorded methods of transmitting information. There is a limit to the amount of data that can be set out on an engineering drawing, and the designer must use his judgment as to what additional information he should provide, either as written specifications or special instructions. It is difficult to generalize on this subject, but it is often the case that the cost of spoilt work due to misunderstandings and poor communications exceeds the cost of giving clear, unambiguous information in the first place.

Effective communications are essential in engineering design. Too often, effort is wasted because information is withheld from the designer or because he fails to express clearly his conception of the product. The designer's approach to his work should include the recognition and elimination of these faults.
CHAPTER 3.

THE ENGINEERING APPROACH TO DESIGN

3.1. INTRODUCTION

This chapter is devoted to a consideration of important tools available to the design engineer to assist him maximise the effectiveness of his design. It deals with the use of mathematics in a quantitative description of three major design problems: (1) the planning of a series of related products, (2) the optimization of design, and (3) designing for product reliability. These subjects are discussed at some length here because of their wide significance in engineering design.

The chapter begins with a study of mathematical models and archetypes, as it is the use of these tools which helps to distinguish engineering design from other less technical design activities. This is followed by a section describing the planning of a series of related products; the question is examined how such a series should be planned in order to provide the best range of performance consistent with reasonable costs. An investigation is then made into the subject of optimum design, and the methods available for optimization are reviewed. The final section deals with the subject of product reliability and points out how this can be estimated at the design stage; the ways in which reliability can be designed into a product are described.

It will be seen that while the previous chapter discussed some of the basic characteristics of design, this chapter has been written specifically with regard to engineering, to consider several important tools which can be used by the design engineer to attack a wide variety of problems.

3.2. MATHEMATICAL MODELS AND ARCHETYPES

Engineers use models to obtain information concerning the performance and appearance of a new product and of its major components during the early stages of design, before the expense of building a full-scale prototype is incurred. The use of physical models is well known. One of the most widely used is the wooden "mock-up" of a product to assist determination of its aesthetic appeal or for use in studying package or installation problems. Another modelling technique is the use of wind tunnels and towing tanks in the testing of scale models of air- and seacraft to determine the dynamic characteristics of a particular design. The mechanical analogue is an example of another type of model; it might consist of a set of connected springs and weights to simulate the vibration characteristics of an airframe or machine tool.
In addition to physical models such as these, the construction of abstract mathematical models or archetypes is often a very valuable design tool. The archetypes are derived largely from the idealizations of physical phenomena that constitute the engineering sciences, these idealizations being expressed in mathematical form. The concept of a mathematical model can be described by a block diagram as in fig. (3.1). The inputs consist of design and environmental variables and the outputs are the performance characteristics of the design concept. The model itself expresses the relation between the inputs and outputs and may consist of algebraic equations, differential equations, graphs, tabular data, or almost any type of mathematical statement.

The use of a mathematical model differs from the usual type of analytical design calculation in that with the model one starts with the design variables and calculates the performance characteristics for any given set of environmental inputs. On the other hand with the usual analytical design calculation one starts with a given set of environmental variables and desired performance parameters and calculates the necessary design variables. For maximum utility the model should be so formulated that it is possible to vary the values of the inputs at will without changing the form of the model.

As an example to illustrate this approach, consider the design of a hydrodynamically lubricated journal bearing of the full $360^\circ$ type. Conventional lubrication theory enables the mathematical model to be set up. This theory is an idealization of the physical problem in which a number of assumptions are made, the most important ones being that the lubricant is a Newtonian liquid, incompressible, weightless, of constant viscosity, and that the flow of lubricant in the bearing is laminar and continuous. The model then consists of relations between the following inputs and outputs

**Inputs:**
- (a) Design variables
  - journal radius $R$
  - bearing length $L$
  - bearing clearance $C$

- (b) Environmental
  - bearing pressure $P$
  - rotational speed $\omega$
  - effective viscosity of lubricant $\mu$

**Outputs:**
- Minimum oil film thickness $h_0$
- or eccentricity ratio $e$, where $h_0 = c(1-e)$
- friction tongue $M$
- heat generated $H$

The derivation of the relations between the inputs and the outputs is given in many standard texts. The commonest system of units employed is the inch-pound-second when these relations take the following form.

$$P = \frac{\mu \omega L}{c^2} \cdot \frac{e}{2(1-e^2)^2} \left\{ \pi^2 (1-e^2) + 16e^2 \right\}^{\frac{1}{2}}$$  \hspace{0.5cm} (3.1)
These equations for load, friction, and heat rate constitute the mathematical archetype of the bearing. By manipulating them the performance of any specific bearing design can be predicted. In particular, if this archetype can be combined with a criterion function such as minimisation of $M$, then we have a basis for determining a preferred design.

It will be realised from this discussion that mathematical modelling techniques are subject to important qualifications. A mathematical model can only be used if adequate mathematical relationships are formulated to describe the design, and if there is sufficient quantitative information available on the operating characteristics and performance of the design and on the environment within which it will function. A mathematical model should be used if there is reasonable assurance that time and cost in reaching the objectives will be saved and the final product will be better than if other possible design techniques were used.

The number of possible variations in the types of design problem for which mathematical modelling techniques are useful is so great that it is not possible to be specific about procedures for using the models. However, it should be emphasised that a logical plan for their use is vital, a disorderly approach can be extremely wasteful.

One technique sometimes used is the "scattershot" approach in which performance is investigated for all combinations of possible values of the input parameters. In effect all possible designs for all possible operating conditions are evaluated and the best one selected. For even a small number of design variables this procedure becomes very cumbersome. To shorten the work an approach sometimes adopted is to investigate randomly selected combinations of values of the variables; in this case, however, evaluation becomes more complicated. A more subtle procedure is the "individual parameter variation" technique, in which the effect of a range of values of one variable at a time is investigated starting from some initially assumed set of design and operating variables. The values of each of the design parameters giving the best performance over the range of operating variables are combined to form a new starting configuration for which the procedure can be repeated. The degree of success with this procedure depends on the degree of interaction between the variables. If the interaction is not too great, it should be possible to converge on an optimum design. We will return to the idea of using mathematical models for optimizing design in section (3.4) below.

With the progressive development of computers we may expect the use of mathematical archetypes to increase. In the past it was generally
uneconomic to explore an archetype except for the most critical design problems, and there was little incentive for the designer to construct such archetypes or to develop the necessary analytical skills. It was usually cheaper to build a preliminary prototype and explore its characteristics experimentally. Now that many designers have computers at their disposal, it has become more economical in time, effort and cost to carry analytical techniques much further. Moreover, it is often possible to explore several alternative ideas with little extra cost.

Computers can be used in many ways to support design activity. For a type of part that is used repeatedly a general archetype can be established and programmed as a special routine for a computer. This programme can make provision for accepting any reasonable set of input variables and output requirements for any suitable criterion function. The output from the computer would then be the optimal set of design parameters and performance characteristics of the part. Such automated design is possible for common machine elements, structural members, fasteners, and so on. For example, the design of the bearing described by equations (3.1), (3.2) and (3.3) could be programmed to give directly the optimum solution for any specified design situation.

The concept of automated design can be extended to components and even to complicated devices. This is currently being done by manufacturers of large electrical equipment for high-power transformers and rotating electric machines. Whether or not to automate a design is a matter of economics: the cost of preparing a large computer programme is a heavy investment. However, it is clear that the computer will play an ever-increasing role in engineering. It will make great demands on the higher levels of analytic skills; it will displace designers whose work is mainly repetitive, and place a greater premium on creative and inventive design.

With or without computers, mathematical modelling techniques remain a powerful design tool when properly applied. Their usefulness depends on the validity of the model, the extent to which any simplifying assumptions introduced lead to significant errors. The utility of a mathematical model does not end when the prototype is built and tested. The model and the prototype can be improved together, using test results to improve the model and using the model to determine the design changes necessary to improve the prototype. In this way a good design tool can be improved to give a better attack on future design problems of the same type.
3.3 PLANNING A MACHINE SERIES

3.3.1 General

In this section we shall consider the planning of a family of related products similar in construction, operation and purpose, which are to be classed together according to a plan which establishes the smallest and largest unit and the rate of increase of the size and rating of intermediate units. While the methods discussed are of general applicability, the specific cases studied will be drawn from the field of mechanical engineering where these ideas can be used in the planning of series of products such as engines, pumps turbines, compressors, fans, gearboxes and many other machines.

In the initial stages of planning, it is usually sufficient to define the performance characteristics and basic geometrical dimensions of all the models without developing each model to finished form. Later, individual units can be developed according to market needs. It is important that the designer avoid the consequences of an unplanned approach in which models are piled on models in the belief that the range is being covered intelligently merely because each model is larger than the one preceding or smaller than the one following. At the outset it may be difficult to set the maximum and minimum sizes of the product series because of lack of knowledge of future market trends. However, the consequences of an initial mistake in setting limiting sizes are not serious because the series can readily be extended in both directions without affecting the intermediate models already established. Of crucial importance are the magnitudes of the intervals between successive models and the variation of these intervals. Short intervals are desirable because they allow a better coverage of possible performance requirements; on the other hand, larger intervals lead to a smaller number of models and lower fixed costs. The best answer is a compromise between these opposing views so that for each region of the series the optimum sizes of interval and number of models are determined.

3.3.2 The Basis of the Plan

A necessary condition for the formation and design of a series of machines is that the units be mutually comparable. There must be some performance criterion which is kept constant throughout. For example, in the field of turbomachinery this might be angular velocity of the rotor, peripheral velocity of the rotor, head, or specific speed.

The performance and size of each machine must be clearly represented; this is done by means of two reference numbers or "modules". The "operational module" represents the capacity or rating of each machine referred to the most suitable property or performance characteristic.
The "geometrical module" represents the geometric size of the machine in terms of the most appropriate dimension of length, area, volume, etc.

The two modules must be inter-dependent so that when one has been arranged in a series, the series formed by the other is automatically determined. The most common and useful form of relationship is

$$Y = a X^b$$

where

- $X =$ geometrical module
- $Y =$ operational module
- $a, b =$ constants for a particular series.

Now modules may be arranged in several types of planned progression, viz., arithmetic progression, geometric progression or a developed geometric progression. Arithmetic progressions are simple, and have certain obvious applications, e.g., number of engine cylinders, number of stages in a pump or compressor. Geometric progressions are widely used, particularly as preferred numbers. In standard series of preferred numbers the ratio of successive terms is a root of ten : $10^{1/5} = 1.585, \ 10^{1/6} = 1.259, \ 10^{1/7} = 1.120, \ 10^{1/8} = 1.058$. Geometric progressions can be further developed to assist the rational planning of machine lines on a more fundamental basis. Thus a second order geometric progression is constructed in the following manner.

Series :

<table>
<thead>
<tr>
<th>$a_1$</th>
<th>$a_2$</th>
<th>$a_3$</th>
<th>…</th>
<th>$a_{n-1}$</th>
<th>$a_n$</th>
</tr>
</thead>
</table>

Number of terms : $1 \ 2 \ 3 \ \ldots \ \ldots \ n-1 \ n$

1st ratio : $r_1 \ r_2 \ \ldots \ \ldots \ r_{n-1}$

2nd ratio (constant) : $\rho \ \rho \ \ldots \ \rho$

Then

$$r_{n-1} = r_1 \rho^{(n-2)}$$

$$a_n = a_1 r_1^{(n-1)} \rho^{(n-1)(n-2)/2}$$

$$a_n = a_1 (r_1 \ r_{n-1})^{(n-1)/2}$$

where

- $a_1 > 0$
- $r_1 > 1$
- $r_{n-1} > 1$
- $0 < \rho < 1$

Tables of second order G.P.'s have been compiled which provide a wide variety of planned progressions, and which can be consulted during preliminary design work.

The use of a planned progression ensures that a family of products is designed whose most important operating characteristics are arranged according to a rational scale. This is achieved through a systematic arrangement of the different units in the group according to their size which in turn depends on a planned series of geometrical modules.
3.3. The Number of Models in the Series:

Performance versus Costs of Production.

While each model of the product is designed for a certain performance it will also often have to cover a range of performances. The extent of this range depends on how quickly its performance deteriorates at off-design conditions away from the original specification. In planning the product line this deterioration has to be balanced against the extra production costs of increasing the number of models. This is a difficult problem and its solution usually rests with the judgment and experience of the designer.

In many cases the interval between adjacent members of the series is determined by considerations of product performance. Thus suppose a series of machines is to be planned to cover a continuous range of duties, there being a finite number of machines spaced at discrete intervals over this range. Each machine is designed for one duty but will be used to cover neighbouring duties as well; away from its design point it suffers a deterioration in performance, there being a reduction in some desirable performance characteristic. This is shown in fig.(3.2) where the spacing between adjacent machines in the series, A and B, depends on the rate at which this deterioration takes place. As A and B are of similar design it can safely be assumed for preliminary work that their performance curves are of the same shape; the ratio of the operating modules at the end of the operating ranges are then

$$\frac{B_2}{B_1} = \frac{A_2}{A_1}$$

The interval between machines A and B is defined by $$\frac{B_0}{A_0}$$, the ratio of their operating modules at their design points.

Then

$$\frac{B_0}{A_0} = \frac{B_2}{B_1} = \frac{A_2}{A_1}$$  \hspace{1cm} (3.8)

In this way the interval between adjacent models is found in terms of the operating characteristics of one of them, and this in turn has been determined by the permissible drop-off in some desirable performance parameter as shown in fig.(3.2).

However, the influence of production costs has also to be considered. How this may be done is illustrated in the following somewhat idealised example. It is required to determine the series of minimum total cost for a case where :

(a) The total number of all machines to be manufactured is approximately 600, which is sufficient to recover all fixed charges. The total cost of manufacturing these machines is the sum of the fixed costs for drawings, patterns, tools etc. and the actual production costs in the factory.

(b) The geometrical modules of the models in the machine series are arranged in geometric progression using preferred numbers, the ratio of the largest geometrical module to the
smallest being 10 to 1. We will investigate possible series of geometric modules having 6, 11, 21, and 41 terms, i.e., basing on standard preferred numbers using the fifth, tenth, twentieth, and fortieth costs of ten.

(c) The cost of production of each model is assumed to be proportional to the square of some typical dimension, hence to the square of the geometrical module. While this is a reasonable assumption, in practice a more precise relation could easily be obtained from cost records. With regard to fixed costs, two cases will be considered,

(i) fixed cost = 3 times unit production cost,
(ii) fixed cost = 10 times unit production cost.

(d) The expected variation of the sales of the different models is shown in fig.(3.3).

The total cost is then calculated for each series; details of the calculations for the 11-term series are tabulated below, and for other series are handled in a similar fashion.

<table>
<thead>
<tr>
<th>Series of Geometric Modules</th>
<th>Cost of Production per Term</th>
<th>Number of Units Sold</th>
<th>Total Production Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Term Module</td>
<td>Module</td>
<td>Unit</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>1.00</td>
<td>1</td>
<td>12</td>
</tr>
<tr>
<td>2</td>
<td>1.25</td>
<td>1.6</td>
<td>67</td>
</tr>
<tr>
<td>3</td>
<td>1.60</td>
<td>2.5</td>
<td>89</td>
</tr>
<tr>
<td>4</td>
<td>2.00</td>
<td>4</td>
<td>99</td>
</tr>
<tr>
<td>5</td>
<td>2.50</td>
<td>6.3</td>
<td>95</td>
</tr>
<tr>
<td>6</td>
<td>3.15</td>
<td>10</td>
<td>84</td>
</tr>
<tr>
<td>7</td>
<td>4.00</td>
<td>16</td>
<td>61</td>
</tr>
<tr>
<td>8</td>
<td>5.00</td>
<td>25</td>
<td>38</td>
</tr>
<tr>
<td>9</td>
<td>6.30</td>
<td>40</td>
<td>24</td>
</tr>
<tr>
<td>10</td>
<td>8.00</td>
<td>63</td>
<td>14</td>
</tr>
<tr>
<td>11</td>
<td>10.00</td>
<td>100</td>
<td>7</td>
</tr>
</tbody>
</table>

Case Fixed Cost | Cost of Production Total Cost |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>(i) 269.4 x 3</td>
<td>5,663</td>
<td>7,470</td>
</tr>
<tr>
<td>(ii) 269.4 x 10</td>
<td>2694</td>
<td>9,360</td>
</tr>
</tbody>
</table>

Fig.(3.4) shows the final results, smooth curves being drawn through the individual points obtained from these calculations. The curves of total cost versus number of models are fairly flat but have distinct minima at between ten and fifteen models. Although this investigation has been based on several assumptions regarding costs and forecast sales, it can nevertheless be used as a guide in the preliminary planning of a machine series. A series having a ratio of geometrical modules of ten should have between ten and fifteen models in order to keep the total cost of manufacture near its minimum value.
Other commercial considerations enter an analysis of this problem beside costs of manufacture. These are less easily defined but on the whole they favour increasing rather than reducing the number of models. The chief reason for this statement is that a manufacturer with a dense product line is better able to offer machines with performances near those requested by the buyer. A manufacturer with a small number of models will occasionally have to offer larger and more expensive machines to meet buyer specifications because of the larger intervals in his less dense line. This fact is easily overlooked because of the difficulty in distinguishing business lost from a faulty series from that lost for reasons of a more directly commercial nature. To some extent the advantages of a dense series tend to be counterbalanced by negative factors, such as stagnation of capital tied up in stocks and other charges which partly depend on the number of models. These also require careful consideration.

3.3.4. Planning a Series of Gearboxes.

To illustrate these ideas, consider the planning of a series of single-reduction, helical gearboxes. The description will be as brief as possible as it is not intended to enter into details of gear design but to given an example of rational planning.

In this case the geometrical module is the centre distance between mating gears, noting that in any one size of housing various transmission ratios may well be possible with the same distance between centres.

The operating module will depend on the power transmission capacity of a gearbox, which is a function of
(a) housing size
(b) gear quality (material and heat treatment)
(c) transmission ratio
(d) rotational speed.

Housing size and gear quality being fixed, the operating module will depend on the latter two variables, transmission ratio and speed.

Resistance to wear is made the basis of calculating the gear transmission capacity \( P \), and this is a function of gear material and general gear dimensions, pitch diameter, face width, tooth curvature. Tooth thickness, radial height and strength need only be considered in checking the maximum allowable tangential tooth load, which is a measure of the danger of failure of the gear teeth in bending. A commonly used relation for \( P \) is

\[
P = k_k_k_D_p F_v
\]

where \( D_p \) = pitch diameter of pinion
\( F \) = effective face width
\( k_v \) = dynamic load factor
\( k_z \) = factor based on transmission ratio \( \alpha \)
\( K \) = coefficient depending on materials and other factors; this is constant for a homologous series of gears.
\( v \) = pitch line velocity.
Now \( P \) is approximately proportional to \( C^3 \). But since \( k_v \) decreases as \( D_p \) and \( v \) increase, a more accurate relation is obtained by reducing the power of \( C \) slightly below three. As a basis for general analysis the following similarity law for gear reducers can be used.
\[
P = f_m f_p \delta g^{2.75}
\]
where \( f_m = \text{factor based on transmission ratio} \), \( f_p = \text{factor based on pinion speed} \), \( n_p \), \( \delta = \text{factor based on fundamental design criteria} \).

For single reduction units
\[
f_m = \frac{1.004}{m} - .004m
\]
\[
f_p = \left(\frac{n_p}{100}\right)^{0.875} \text{ for } 100 < n_p < 2000 \text{ r.p.m.}
\]

For steel herringbone gears, 300 B.H.N., \( 30^\circ \) helix angle, \( 20^\circ \) pressure angle,
\[
\delta = 0.70 \text{ to } 0.115
\]
The low value of \( \delta \) applies to large units and the high value to small units. In intermediate sizes \( \delta \) is approximately 0.10. Then the specific rating of the gear reducer \( P_0 \) is defined as the value of \( P \) corresponding to a selected reference condition, say \( m = 1 \), \( n_p = 100 \), so that
\[
P_0 = \delta C^{2.75} \quad (3.9)
\]
This equation expresses the operating module in terms of the geometrical module and forms the basis for planning the series.

Suppose that a series of double helical, single reduction gear reducers is to be designed to cover the range:
specific power rating - 4 to 2,500 h.p.
transmission ratio - 1.25 to 10.

In setting out the series trial calculations will first be necessary to check approximate values of smallest and largest centre distances and smallest and largest gears to ensure that these suit available manufacturing capacity.

\( \delta \) can be taken as 0.10 initially but as the calculations progress it should be allowed to vary with the size of unit. A suitable progression has to be determined for the specific ratings giving an overall ratio of \( 2500/4 = 625 \). The designer may judge that the maximum allowable ratios for the progression of the specific ratings would be approximately as follows:
- 10 h.p. - 2
- 100 h.p. - 1.5
- 1000 h.p. - 1.25
- 2500 h.p. - 1.10

With the assistance of tables of second order geometric progressions the
line of gear reducers is then developed as shown in the table below.

<table>
<thead>
<tr>
<th>Progression</th>
<th>Terms</th>
<th>Ratios</th>
<th>Fo (h.p.)</th>
<th>Model</th>
<th>S (in)</th>
<th>C (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rate 1</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>Rate 2</td>
<td>1.584</td>
<td>1.584</td>
<td>1.584</td>
<td>1.584</td>
<td>1.584</td>
<td>1.584</td>
</tr>
<tr>
<td>Rate 3</td>
<td>2.147</td>
<td>2.147</td>
<td>2.147</td>
<td>2.147</td>
<td>2.147</td>
<td>2.147</td>
</tr>
<tr>
<td>Rate 4</td>
<td>2.503</td>
<td>2.503</td>
<td>2.503</td>
<td>2.503</td>
<td>2.503</td>
<td>2.503</td>
</tr>
<tr>
<td>Rate 5</td>
<td>2.865</td>
<td>2.865</td>
<td>2.865</td>
<td>2.865</td>
<td>2.865</td>
<td>2.865</td>
</tr>
<tr>
<td>Rate 7</td>
<td>3.561</td>
<td>3.561</td>
<td>3.561</td>
<td>3.561</td>
<td>3.561</td>
<td>3.561</td>
</tr>
<tr>
<td>Rate 8</td>
<td>3.888</td>
<td>3.888</td>
<td>3.888</td>
<td>3.888</td>
<td>3.888</td>
<td>3.888</td>
</tr>
<tr>
<td>Rate 11</td>
<td>4.598</td>
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<td>4.598</td>
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</tr>
<tr>
<td>Rate 13</td>
<td>4.939</td>
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<tr>
<td>Rate 14</td>
<td>5.064</td>
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<td>5.064</td>
<td>5.064</td>
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</tr>
<tr>
<td>Rate 15</td>
<td>5.165</td>
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<td>5.165</td>
<td>5.165</td>
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</tr>
<tr>
<td>Rate 16</td>
<td>5.245</td>
<td>5.245</td>
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<td>5.245</td>
<td>5.245</td>
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</tr>
<tr>
<td>Rate 17</td>
<td>5.305</td>
<td>5.305</td>
<td>5.305</td>
<td>5.305</td>
<td>5.305</td>
<td>5.305</td>
</tr>
<tr>
<td>Rate 18</td>
<td>5.346</td>
<td>5.346</td>
<td>5.346</td>
<td>5.346</td>
<td>5.346</td>
<td>5.346</td>
</tr>
</tbody>
</table>

After the series of gearboxes has been laid out in this way the detailed design of the individual units can be undertaken. It will be noticed that in this series, the ratio of ten in centre distances is covered by 16 terms, 3.61 in. to 36.8 in.; this result is slightly on the high side according to Fig. (3.4) but is fully justifiable on the grounds that the product line is composed of gear reducers intended for general sale.

3.3.5. Planning a Series of Centrifugal Pumps.

Consider now the planning of a series of centrifugal pumps for the following range of duties.

- **Capacity**: 1,100 g.p.m. to 25,000 g.p.m.
- **Head**: 40 ft.

Many manufacturers have a standard range of pumps for capacities up to 1,000 g.p.m. and this new series would extend the range to higher capacities at the constant head of 40 feet, a value often encountered in applications where it is required to circulate large quantities of water for cooling purposes.

In order to establish the modules and the relation between them it will be first necessary to consider briefly the technology of turbo-machinery. A centrifugal pump consists essentially of a rotating element which imparts energy to a moving stream of water, and discharges it through a stationary casing which converts most of the kinetic energy of the water leaving the rotor to pressure energy. The important performance character-
istics are - rotational speed \( N \), capacity \( Q \), and head \( H \); these can be combined into a non-dimensional parameter, the specific speed \( N_s \), which is an index of pump type.

\[
N_s = \frac{N \sqrt{Q}}{H^{\frac{3}{2}}} \tag{3.10}
\]

In a series of geometrically similar pumps the specific speed is constant and

\[
\frac{Q}{H} \propto N D^2 \tag{3.11}
\]

where \( D \) is the rotor diameter. Similar relations also hold for other types of turbomachines handling incompressible fluids. Other important characteristics are efficiency \( \eta \) and the power absorbed by the pump \( P \).

The planning of a series of pumps could be based on constant specific speed, constant rotational speed, or constant rotor tip speed. In this instance we will assume as the basis for planning that all pumps are to be geometrically similar, having the same specific speed, and that a suitable model exists which is known to have the following characteristics.

\[
\begin{align*}
Q_0 &= 2,000 \text{ g.p.m.} \\
n_0 &= 85.0\% \\
H &= 40 \text{ ft.} \\
N &= 1,450 \text{ r.p.m.} \\
P &= 28.5 \text{ h.p.} \\
D &= 9" \\
\eta &= 0.95 \text{ when } \frac{Q}{Q_0} = 0.685 \text{ and } 1.262 \\
\eta &= 0.90 \text{ when } \frac{Q}{Q_0} = 0.761 \text{ and } 1.183
\end{align*}
\]

Quantities having the subscript "o" refer to conditions at the design or best efficiency point.

The operating range of each pump in the series depends on the permissible drop in efficiency, which must be set by the designer on the basis of his previous experience. In general, the larger the pump the more power it consumes, and the more important its operating efficiency becomes. It will be assumed here that the drop in efficiency that can be allowed will be 10% for the smallest pump and 5% for the largest. Since all pumps are of similar design the curve of \( \eta / \eta_0 \) versus \( Q / Q_0 \) will be the same for each.

The series of centrifugal pumps can now be laid out. The operating module is capacity, the geometrical module is rotor diameter, and from equation (3.11) the relation between them is

\[
Q \propto D^2 \tag{3.12}
\]

From the data on efficiencies and using the result established in equation (3.8) it is possible to determine the first and last series ratios in the series of operating modules.

\[
\begin{align*}
\text{First series ratio} &= \frac{1.262}{0.685} = 1.842 \\
\text{Last series ratio} &= \frac{1.183}{0.765} = 1.550
\end{align*}
\]
It is now required to find a suitable progression for the geometrical modules; this progression must satisfy these conditions.

\[ \frac{a_n}{a_1} = \sqrt[10]{\frac{25,000}{1,100}} = 4.77 \]

\[ r_1 = \sqrt[10]{1.842} = 1.357 \]

\[ r_{n-1} = \sqrt[10]{1.550} = 1.285 \]

By manipulation, a suitable second order G.P. is found with

\[ n = 7; \quad \rho = 0.983. \]

<table>
<thead>
<tr>
<th>Item</th>
<th>Geometric Module Progression</th>
<th>Operating Module Progression</th>
<th>Capacity (g.p.m.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.00</td>
<td>1.00</td>
<td>1,100</td>
</tr>
<tr>
<td>2</td>
<td>1.56</td>
<td>1.84</td>
<td>2,000</td>
</tr>
<tr>
<td>3</td>
<td>1.84</td>
<td>3.28</td>
<td>3,600</td>
</tr>
<tr>
<td>4</td>
<td>2.37</td>
<td>5.62</td>
<td>6,200</td>
</tr>
<tr>
<td>5</td>
<td>3.05</td>
<td>9.30</td>
<td>10,300</td>
</tr>
<tr>
<td>6</td>
<td>3.50</td>
<td>14.97</td>
<td>16,500</td>
</tr>
<tr>
<td>7</td>
<td>4.32</td>
<td>23.20</td>
<td>25,500</td>
</tr>
</tbody>
</table>

It will be seen that eleven terms cover the ratio of geometrical modules of ten to one. This is probably on the low side, indicating that the reductions in efficiency originally allowed were too high. However, in practice any gaps would be filled by having two or more alternative designs of rotor fit the same stator casing.

Further calculation gives the following range of pumps which cover the performances shown in fig. (3.5).

<table>
<thead>
<tr>
<th>Item</th>
<th>Head (ft.)</th>
<th>Flow (g.p.m.)</th>
<th>N</th>
<th>D (in)</th>
<th>Estimated Efficiency</th>
<th>Power - h.p.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(ft.)</td>
<td>(g.p.m.)</td>
<td>(r.p.m.)</td>
<td>(in)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>40</td>
<td>1,100</td>
<td>1,970</td>
<td>6.6</td>
<td>84.5</td>
<td>15.8</td>
</tr>
<tr>
<td>2</td>
<td>40</td>
<td>2,000</td>
<td>1,450</td>
<td>9.0</td>
<td>85.0</td>
<td>28.5</td>
</tr>
<tr>
<td>3</td>
<td>40</td>
<td>3,600</td>
<td>1,090</td>
<td>12.0</td>
<td>85.7</td>
<td>51</td>
</tr>
<tr>
<td>4</td>
<td>40</td>
<td>6,200</td>
<td>830</td>
<td>15.7</td>
<td>86.4</td>
<td>88</td>
</tr>
<tr>
<td>5</td>
<td>40</td>
<td>10,300</td>
<td>645</td>
<td>20.2</td>
<td>87.2</td>
<td>143</td>
</tr>
<tr>
<td>6</td>
<td>40</td>
<td>16,500</td>
<td>510</td>
<td>25.6</td>
<td>88.0</td>
<td>227</td>
</tr>
<tr>
<td>7</td>
<td>40</td>
<td>25,500</td>
<td>410</td>
<td>31.9</td>
<td>88.5</td>
<td>350</td>
</tr>
</tbody>
</table>

If the pumps are to be direct coupled to electric motors, the problem becomes more complicated. The simplest approach is to take the motor speed nearest to that previously determined. This will give a close degree of similarity in the hydraulic designs of the last six pumps.
but the first pump in the series would be significantly different, as is shown by a comparison of the specific speeds set out in the table below.

<table>
<thead>
<tr>
<th>Item</th>
<th>Constant $N_s$</th>
<th>Electric Motor Drive</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$N_s$ (r.p.m.)</td>
<td>$N_s$ (U.S. units)</td>
</tr>
<tr>
<td>1</td>
<td>1,970</td>
<td>3,510</td>
</tr>
<tr>
<td>2</td>
<td>1,650</td>
<td>2,000</td>
</tr>
<tr>
<td>3</td>
<td>1,090</td>
<td>4,000</td>
</tr>
<tr>
<td>4</td>
<td>650</td>
<td>2,000</td>
</tr>
<tr>
<td>5</td>
<td>510</td>
<td>4,340</td>
</tr>
<tr>
<td>6</td>
<td>410</td>
<td>4,600</td>
</tr>
</tbody>
</table>

The methods discussed here for a range of pumps for constant head can be further extended to deal with the planning of ranges of pumps with varying heads as well as varying capacities. This extension requires a fairly detailed knowledge of pump design; and for this reason will not be described.

3.3.6. Conclusion.

Two examples have now been given of how a family of similar machines should be planned. If sufficient care and trouble are taken in the early stages of the design of a series of related products, a logical plan can be established which combines good overall performance with economic production costs. It happens frequently that new designs are added to a series in an unplanned, haphazard fashion in response to the importunings of salesmen, without regard to the true needs of the situation.

Wherever possible a policy of family resemblance in appearance should be adopted, in the design of complex products as well as for consumer goods. If all machines in a series are alike in appearance, the range then has a measure of uniformity so that any one machine is easily recognizable as a product of the same manufacturer. Family resemblance can often be promoted by standardizing some design features, a process which is doubly advantageous because it also assists economic production.

3.4. OPTIMUM DESIGN.

3.4.1. General.

Every design has to fulfill the criterion of adequacy, it must work. But in these days of advanced technology and highly competitive markets mere adequacy no longer satisfies as a design criterion. Out of all possible designs it is necessary to find the best, and for this purpose more stringent criteria than simple adequacy are required.

In a particular case the designer has to select certain parameters, the design variables. It is logical to suppose that among all
feasible combinations of values of the design variables, there is one superior to all the others - the optimum design. This optimum can be arrived at in several ways: through trial and error by modifying successive generations of design, by experimental methods in which parameters are changed in a consistent fashion so that the feasible parameter space can be explored, by computer simulation which is an abstract counterpart of the experimental method, and by mathematical means in which an archetype is constructed and used to isolate the optimum. It is this last method based on the use of mathematical models which will be considered here.

As soon as the problem is raised of determining which of the feasible solutions is best, it is necessary to state precisely how the quality of excellence is to be judged. The use of the word "good" implies a value judgment and such judgments only have meaning in reference to criteria. The attributes of the design to be considered in the process of optimization must be defined, their method of measurement specified, and their relative importance established. The result is a composite statement, the criterion for optimization of design. If the optimization is to be performed mathematically, this statement is expressed in the form of an equation, "the criterion function". Typical criteria in use today are minimum weight, minimum cost, and maximum profit.

Sometimes a design criterion is set for a subordinate element without taking into account the higher design objectives of the system as a whole. The designer should realize that sub-optimization of this part of the system may or may not fit reasonably well with the rest of the system depending on the degree of interaction between the component parts. A recent paper before the Institution of Mechanical Engineers studied the optimum design of the condenser circulating water system of a power station. Since the condenser and its auxiliaries form a self-contained unit this was a legitimate example of sub-optimization.

A design can only be optimized under one criterion. If there are several criteria under which we would like to optimize the design some compromise must be made. One way of doing this is to set up a composite criterion in which each of the component criteria is given a relative weighting, thus establishing in effect a single criterion. Another is to convert the less important criteria into constraints by giving them some upper or lower limits of acceptance. In practice, this means that the optimization will be accomplished while the design is pushed to the acceptance limits of the sub-criteria.

3.4.2. First Statement of the Optimization Problem.

Consider the case where a mathematical model for the design has been set up. Let \( X_1, X_2, \ldots, X_i, \ldots, X_n \) represent the \( n \) inputs to this model, and \( Y_1, Y_2, \ldots, Y_j, \ldots, Y_m \) represent the \( m \) outputs. The \( X \)'s consist of design variables to be selected by the designer and environmental inputs imposed by the data of the problem. The \( Y \)'s consist of the attributes of the design which are to be studied; these may include
economic factors and costs as well as technical performance characteristics. The mathematical model establishes the relations between each \( Y \) and the set of \( X \)'s.

The constraints on the design impose limits on the permissible values which the input and output variables may take. Moreover, each \( X \) may vary continuously over its range or it may be limited to a finite number of values corresponding to the number of materials which may be used or the standard sizes available. It is assumed that each \( X \) is independent of the other \( X \)'s and that each \( Y \) can be expressed as an explicit function of some or all of the input variables. The first statement of the optimization problem then takes the following form.

**Criterion**: Selected \( Y \) or combination of \( Y \)'s to be maximum or minimum.

**Model**: \[ Y_j = f_j(X_1, \ldots, X_n) \]

\( j = 1, 2, \ldots, m \)  \hspace{10cm} (3.13)

**Constraints**: \[ a_i \leq X_i \leq b_i \]

\[ A_j \leq Y_j \leq B_j \]

A series of examples of increasing complexity will now be discussed to show how these ideas may be applied.

**Case (1). Systems with One Design Variable, One Output Variable.**

This is the simplest case and is important because in practice many complex systems can be reduced to it by making suitable assumptions. We have then:

\[ Y = f(X) \text{ to be optimum} \]

\[ a \leq X \leq b \]

\[ A \leq Y \leq B \]

Fig. (3.6) illustrates this for the case where \( Y \) is to be a minimum. The position of the optimum design point depends on the limiting values of \( X \) and \( Y \). For the conditions shown in fig. (3.6) the optimum design is not at \( Q \) where \( \frac{dY}{dX} = 0 \) but at \( P \).

As a specific example, suppose it is desired to find the optimum proportions of a bulk storage tank of given volume. The usual notation for this problem is as set out below.

- \( D \) = diameter of tank
- \( H \) = height of tank
- \( A_1 \) = area of shell, \( \pi DH \)
- \( A_2 \) = area of bottom, \( \pi D^2/4 \)
- \( V \) = volume of tank, \( \pi D^2H/4 = A_1D/4 \)
- \( c_1 \) = annual cost of fabricated shell per unit area
- \( c_2 \) = annual cost of fabricated bottom per unit area
- \( c_3 \) = annual cost of fabricated roof per unit projected area
- \( c_4 \) = annual cost of installed foundations per unit area of tank bottom
- \( c_5 \) = annual cost of land in tank area chargeable to tank, per unit area of tank bottom
- \( C \) = total annual cost.
The criterion for optimizing the design is that $C$ is to be a minimum.

The mathematical model is obtained by putting

$$C = A_1 c_1 + A_2 (c_2 + c_3 + c_4 + c_5)$$

$$C = \frac{4Wc_1}{D} + \frac{\pi}{4} D^2 (c_2 + c_3 + c_4 + c_5)$$

Now for small tanks it is approximately true that the shell thickness is independent of $D$ and $H$, so that the cost factor $c_1$ can be taken as constant. $c_2$, $c_3$, $c_4$, $c_5$ can also be treated as constants without serious error. The problem is then reduced to one where $C$ is a function of the single design variable $D$, and the optimum design is given by

$$\frac{dC}{dD} = 0$$

whence

$$- \frac{4Wc_1}{D^2} + \frac{\pi}{2} D (c_2 + c_3 + c_4 + c_5) = 0$$

$$\therefore D^3 = \left(\frac{8V}{\pi}\right) \frac{c_1}{c_2 + c_3 + c_4 + c_5}$$

$$\therefore \frac{D}{H} = \frac{2c_1}{c_2 + c_3 + c_4 + c_5}$$

For large tanks $c_1$ will depend on the shell thickness and will be closely proportional to $D$ and $H$, providing the corrosion allowance is ignored. In this case if $c_1 = c_6 DH$, say, the mathematical model becomes

$$C = 4c_5 VH + \frac{\pi}{4} D^2 (c_2 + c_3 + c_4 + c_5)$$

i.e.

$$C = \frac{16V^2 c_6}{\pi} \frac{1}{D^2} + \frac{\pi}{4} D^2 \frac{H}{c_2 + c_3 + c_4 + c_5}$$

$$\frac{dC}{dD} = 0$$

$$\therefore - \frac{32V^2 c_6}{\pi} \frac{1}{D^3} + \frac{\pi}{2} D (c_2 + c_3 + c_4 + c_5) = 0$$

$$\therefore - 2c_1 H + \frac{1}{2} D (c_2 + c_3 + c_4 + c_5) = 0$$

$$\therefore \frac{D}{H} = \frac{4c_1}{c_2 + c_3 + c_4 + c_5}$$

The optimum proportions of the tank can thus be found in terms of the cost factors $c_1$, $c_2$, $c_3$, $c_4$, $c_5$. At the outset the designer has to estimate these factors and then proceed with the detailed design up to a point where they can be checked. If the new values are found to be significantly different from those originally assumed a process of successive approximations must be undertaken to converge onto the optimum design.

Case (2). Systems with One Design Variable, Several Output Variables.

When there are outputs or responses from the model other than the one to be optimized, the additional outputs may impose further constraints.
on the design. Fig.(3.7) has been drawn for a typical case with two outputs $Y_1$ and $Y_2$. The model is represented by

$$Y_1 = f_1(X)$$
$$Y_2 = f_2(X)$$

The constraints are

$$X \leq b$$
$$Y \leq B$$

The criterion function is

$$Y_1 = f_1(X)$$

Then the optimum design is given by the point $P$.

(Case (3). Systems with Two Design Variables.)

Design problems where two variables have to be selected by the designer are conveniently represented in two dimensions by contour plots of the responses as functions of the design variables. If there is only one output to be considered, the optimum design can be found by inspection of the contour plot. If there are additional outputs imposing constraints on the design the optimum point can be found by superposition of the different sets of contours.

Fig.(3.8) illustrates a typical example with two output variables.

The mathematical model is

$$Y_1 = f_1(X_1, X_2)$$
$$Y_2 = f_2(X_1, X_2)$$

The constraints are

$$X_1 \leq b_1, \quad X_2 \leq b_2$$
$$Y_2 \leq B$$

The criterion function is

$$Y_1 = f_1(X_1, X_2)$$

Feasible designs lie in the shaded part of the diagram; the optimum design is given by the point $P$.

This example could apply to the design of a chemical system where

$X_1 = \text{operating pressure}$
$X_2 = \text{operating temperature}$
$Y_1 = \text{cost of process}$
$Y_2 = \text{percentage impurity in product}$

The maximum values of the pressure and temperature, $X_1$ and $X_2$, may be set by constructional limitations; the cost $Y_1$ should clearly be a minimum consistent with acceptable values of percentage impurity $Y_2$.

Case (4). Systems with Several Design Variables, One or Two Output Variables.

Consider the case where a response $Y$ is affected by several design variables $X_1, X_2 \ldots$ The function $Y$ forms a "response surface" and it is necessary to explore the shape of this surface and its contours in order to find the optimum conditions. One method of doing
this is "ridge analysis". In suitable applications this is a powerful approach because it allows a multi-dimensional response surface to be represented on a two-dimensional plot. As this method is not well known a brief description of it will be given here.

Consider a contour plot for two variables, generated by the second degree equation.

\[ Y = b_0 + b_1 X_1 + b_2 X_2 + b_{11} X_1^2 + b_{22} X_2^2 + b_{12} X_1 X_2. \]  

(3.14)

Suppose for example that

\[ Y = 80 + 0.1 X_1 + 0.2 X_1^2 + 0.1 X_2^2 + X_1 X_2 + 0.2 X_2. \]  

(3.15)

Fig. (3.9) shows contours of Y plotted against x1 and x2. It will be seen from this figure that as a vector R sweeps a circle around the origin it detects two maxima and two minima in the value of Y. If this sweeping procedure is repeated for different values of R the loci of the maximum and minimum points form "ridge" lines A, B, C, D. These are the lines of steepest ascent and steepest descent with respect to the origin. No matter where the origin is located these lines will always lead upwards to the top of a hill, or downwards to the bottom of a valley. For a second degree equation such as (3.14) there are always twice as many ridge lines as there are variables in the system. For more than 2 dimensions this topographical analogy loses its meaning, but mathematically we can still think of ridge lines.

The value of the output variable Y and of each of the input variables X1 and X2 can be plotted against the radius R for each ridge line, as shown in fig. (3.10). (There are well-known mathematical procedures for calculating the values of Y and X1 and X2 along ridge lines.) The optimum value of Y can then be determined, hence the corresponding value of R and the values of X1 and X2 which give the optimum result. In this example if the constraints on X1 and X2 in equation 3.15 are such that the maximum value of R is 1.2, then the optimum design is given by

\[ X_1 = 0.85 \]
\[ X_2 = 0.82 \]
\[ Y = 81.2 \]

The advantages of ridge analysis are:

(a) The maximum or minimum of a system always lies on a ridge line.

(b) Regardless of the number of variables in a system each output can be represented on a two-dimensional plot.

(c) Secondary ridge lines can be detected. In some cases the true optimum can lie on a secondary ridge, e.g. when the origin is poorly chosen.

(d) The method can be extended to cover cases where there are multiple outputs some of which are subject to restraints.

A recent paper to the American Society of Mechanical Engineers discussed the application of ridge analysis to the optimum design of an overhung rotor of a typical rotating machine such as an agitator, mixer, pump, or compressor. The design criteria for optimization were maximum
critical speed and minimum weight. The details of the particular rotor studied are shown in fig. (3.11), there being four design variables - three shaft diameters, \( d_1 \), \( d_2 \), \( d_3 \), and the bearing spacing \( l \). The geometrical limits on these variables were as follows.

\[
0.75" \leq d_1 \leq 1.75" \\
1.50" \leq d_2 \leq 2.50" \\
0.50" \leq d_3 \leq 1.50" \\
7.0" \leq l \leq 17.0"
\]

To assist the calculations these variables were coded.

\[
\begin{align*}
X_1 &= 4(d_1 - \bar{d}_1) - 2 \leq X_1 \leq 2 \\
X_2 &= 4(d_2 - \bar{d}_2) - 2 \leq X_2 \leq 2 \\
X_3 &= 4(d_3 - \bar{d}_3) - 2 \leq X_3 \leq 2 \\
X_4 &= 50 \{(1/l) - (1/L)\} - 2 \leq X_4 \leq 2
\end{align*}
\]

The output variables were critical speed \( y_1 \) and shaft weight \( y_2 \).

The mathematical model was constructed in a form giving second degree equations relating the outputs to the inputs.

\[
\begin{align*}
y_1 &= b_0 + b_1 X_1 + \cdots + b_4 X_4 \\
&\quad + b_{11} X_1^2 + \cdots + b_{44} X_4^2 \\
&\quad + b_{12} X_1 X_2 + \cdots + b_{34} X_3 X_4 \\
y_2 &= c_0 + c_1 X_1 + \cdots + c_4 X_4 \\
&\quad + c_{11} X_1^2 + \cdots + c_{44} X_4^2 \\
&\quad + c_{12} X_1 X_2 + \cdots + c_{34} X_3 X_4
\end{align*}
\]

The coefficients \( b_0 \cdots b_{34}, c_0 \cdots c_{34} \) were determined with the aid of computers.

It was then required to optimize the design of the shaft by determining the values of \( d_1, d_2, d_3 \), and \( l \) for two cases,

(a) \( y_1 \) to be maximum

(b) \( y_2 \) to be minimum subject to \( y_1 \leq 6,000 \) r.p.m.

To attack these problems the response ridges for maximum and minimum critical speeds were calculated. These are shown in fig. (3.12) with critical speed along the ridge as a function of the radius measured into "four-dimensional" space. In this case only the main ridges are shown as the secondary ridges were all far outside the ranges of the input variables.

The maximum critical speed could easily be determined as the highest point on the ridge within the range of the design - 8,200 r.p.m. This was in fact 70% higher than that of the original design chosen by rule-of-thumb methods. The corresponding values of the design variables were:

\[
\begin{align*}
d_1 &= 1.70" \\
d_2 &= 2.22" \\
d_3 &= 1.00" \\
l &= 11.78"
\end{align*}
\]

In the second problem it was required to determine the shaft of minimum weight that satisfied the restraint on critical speed. Ridge plots had then to be made for the shaft weight as well as for the critical
speed, fig. (3.13). These showed that the minimum shaft weight within the limits of the design was 5.7 lb., but that the corresponding critical speed was only 4,200 r.p.m. To determine the optimum design it is necessary to find the point nearest the point of minimum weight for which \( Y_1 \geq 6,000 \) r.p.m. This leads to more complicated mathematics which lie outside the scope of this discussion. Only the result will be noted here, namely, \( Y_2 = 7.3 \) lb., a value 30% less than that previously obtained by conventional rule-of-thumb methods.

Although optimization of the design of the rotor shaft was a lengthy process, it led to an overall saving because the rotors were used in chemical equipment produced in relatively large quantities and manufactured from expensive materials.

### 3.4.3. General Statement of the Optimization Problem.

The general statement of the optimization problem is obtained by relaxing some of the previously imposed restrictions. We now consider the case where there are relationships between the output variables as well as between the outputs and inputs to the mathematical model which represents the design.

It is characteristic of engineering design that there is not an unlimited choice of the design parameters. In fact they may be constrained in two ways. First, the design parameters and other variables are connected by natural laws and empirical relations which reflect the behaviour of the product being designed as formulated in the mathematical model. These "functional constraints" express the functional relationships which must hold if the design is to be physically realizable. Secondly, limits may be imposed on individual parameters or on groups of parameters in order to ensure their compatibility with the rest of the system and with the environment. These limits mark out the permissible regions for the design and will be called "regional constraints". Thus the functional constraints will be distinguished by equalities, the regional constraints by inequalities.

The three constituents of the general optimization problem are:

1. the criterion function which is to be brought to a maximum or minimum by proper choice of the design parameters;
2. the functional constraints which essentially constitute the mathematical description of the archetype of the proposed design;
3. the regional constraints, setting allowable limits on parameters or groups of parameters.

Let \( (x_1, \ldots, x_n) \) be the set of input and output variables, there being a total of \( n \) variables.

Let \( (\alpha_1, \ldots, \alpha_m) \) be the set of \( m \) functional constraints.

Let \( (\beta_1, \ldots, \beta_p) \) be the set of \( p \) regional constraints.

Let \( L_i \) and \( U_i \) be the lower and upper limits on the \( i \)th regional constraint.

Let \( C \) be the criterion function.

Then
where
\[ c_1 = \alpha_1 (x_1 \cdots x_n) = 0 \]  
\[ \vdots \]  
\[ c_m = \alpha_m (x_1 \cdots x_n) = 0 \]  
and
\[ l_1 \leq \beta_1 (x_1 \cdots x_n) \leq L_1 \]  
\[ \vdots \]  
\[ l_p \leq \beta_p (x_1 \cdots x_n) \leq L_p \]  

Equations (3.16), (3.17) and (3.18) are the general mathematical statement of the optimization process. It should be noted that for this process to be possible the number of functional constraints must be less than the number of variables, \( m < n \), since if \( m = n \) equations (3.17) will consist of a set of simultaneous equations in \( n \) unknowns, and only one design is possible corresponding to the set of solutions of these simultaneous equations. If \( m > n \) no design is possible except in very special cases of no general interest. On the other hand, there is no theoretical limit to the number of regional constraints, \( p > n \) is possible, although unusual in practice.

By ignoring some of the constraints or simplifying their form, equations (3.16), (3.17) and (3.18) can be converted to a form which is mathematically tractable. The more important analytical techniques by which this may be done will now be investigated, but without delving too deeply into the details of the procedures as these are adequately covered in mathematical texts. The techniques to be considered are: (1) the method of steepest descent, (2) Lagrangian multipliers, and (3) linear programming. The method of steepest descent can be applied when there are no regional constraints and when the functional constraints are expressed explicitly. When the functional constraints involve implicit functions of the design parameters and other variables we can proceed by using Lagrangian multipliers. Linear programming considers the optimization of a linear criterion function subject to a set of linear regional constraints.

(1) Method of Steepest Descent.

In cases where optimization is not subject to regional constraints, and the functional constraints are expressed in a sufficiently simple form, equations (3.17) can be combined with (3.16) to produce a modified criterion function \( C^f \) whose maximum or minimum has then to be found. In geometrical language, the problem is to explore the multi-dimensional surface representing \( C^f (x_1 \cdots x_n) \) for the highest peak or lowest valley depending on which extreme value is optimal. We begin at some convenient starting point, preferably as close to the solution point as we can guess. We then survey the terrain, choose the direction of steepest slope, the gradient, and follow this direction downward (or upward if we seek a maximum).
for some convenient distance. We then resurvey the terrain from the new location, determine the direction of the gradient and repeat until the gradient attains an absolute value of zero. At this point we are presumably at the minimum, at the bottom of a valley, providing the surface was of simple contour. At least three things can happen to contravene a true solution: one, the valley may actually be a local depression, and the true solution would be at the bottom of some other deeper valley; two, the point may be on a ledge, and further travel in the same direction would continue the downward trend; three, the location may be on a saddlepoint, and further travel in some orthogonal direction would continue the downward path. This process of exploration is well suited to computer adaptation, for the gradient at any starting point can be approximated by numerical methods, a new point located at a given increment from the old, and so on. When the surface is suspected to contain several valleys, a suitable statistical design can be applied to the choice of starting points, the region of interest being explored and the optimum finally selected from the set of extreme values.

To complete the solution a check is made that a true minimum (or maximum) has been reached, not just a saddlepoint or ledge. This is done by examining second order and higher partial derivatives. If there is substantial doubt as to whether a point found to be a local minimum is in fact the absolute minimum then a statistical exploration of the surface must be undertaken.

2) Lagrangian Multipliers.

A more general and powerful method of attack is required for solving optimization problems involving functional constraints which are implicit functions of the design parameters and other variables, and we can proceed using Lagrangian multipliers.

The functional constraints \( \alpha_1 \ldots \alpha_m \) provide \( m \) equations in \( n \) unknowns where \( m < n \). By employing Lagrangian multipliers the criterion function is replaced by a set of \( (n - m) \) additional non-linear equations, so that there is then a total of \( n \) simultaneous equations and their solution corresponds to the extremum of the criterion function. The optimum values of \( x_1 \ldots x_n \) are then found and the optimum design established.

In principle, this method produces a solution of the general optimization problem with functional constraints. However, the resulting set of non-linear simultaneous equations can present formidable difficulties in reduction to numerical solutions, and computers may be required to handle the calculations which are often lengthy.

3) Linear Programming.

So far the question of regional constraints has been ignored. However, these constraints occur in an important class of optimization problems which frequently arise in systems design and which involve variables related by linear equations. In the standard form of the linear programming problem, a linear criterion function is to be optim-
ized and a set of linear regional constraints satisfied.

\[ C = c_1 x_1 + c_2 x_2 + \ldots + c_n x_n \] to be optimum

\[ \beta_1 = b_{11} x_1 + b_{12} x_2 + \ldots + b_{1n} x_n \geq L_1 \]

\[ \vdots \]

\[ \beta_m = b_{m1} x_1 + b_{m2} x_2 + \ldots + b_{mn} x_n \geq L_m \]

\[ x_i > 0 \text{ where } i = 1, 2, \ldots, n \] (3.19)

Much effort has been devoted to finding solutions to this type of problem, and there is a wide body of literature on the subject. Linear programming is applied in the oil and chemical industries as a technique for programming operations. It can also be a useful design tool, particularly in the early stages when feasibility studies are being carried out and preliminary designs drawn up.

The subject can be extended to treat some non-linear problems by linear approximations. Another extension of potential interest in design work is parametric linear programming. Essentially this is a sensitivity analysis showing which parameter, if changed, will produce the greatest effect on the design.

In this discussion there has been a general statement of the problem of optimum design, and several important cases have been considered where methods are available for determining this optimum. In the cases examined here the problem has been simplified by ignoring either the functional or the regional constraints, or by assuming that the constraints can be expressed in a special, simple form. The whole subject is being actively investigated by mathematicians, and techniques are being developed to handle problems of increasing complexity.

3.4.4. Optimum Design of Mechanical Elements.

We now consider the application of the ideas of optimum design to a particular field of engineering, the design of mechanical elements. In this context an element is defined as the simplest part which will perform a basic mechanical or structural function, such as the transmission of motion, force or torque. Further insight is gained into the problems of optimisation by examining the design of common elements such as bars, beams and shafts; these are the simplest components in any mechanical design.

The design of a mechanical element consists in the selection of materials and geometry which satisfy specified and implied functional requirements while remaining within the confines of inherently unavoidable limitations. Associated with any mechanical element are certain desirable effects such as capability for transmission of torque or for absorbing overload, and certain undesirable effects such as cost and weight. The simplest way to arrive at an optimum design is to maximise the most significant desirable effect or minimise the most significant undesirable effect.

Design equations express either functional requirements or
undesirable effects in terms of parameters which can be classified according to three basic groups.

(1) Functional requirement (or undesirable effect) parameters.

(2) Material parameters.

(3) Geometrical parameters.

The functional requirement parameters in a design equation are usually specified from an analysis of the complete mechanical structure before the design of the element is undertaken. The group of specified functional requirement parameters is independent of both the material parameter group and the geometrical parameter group.

Material parameters are not independent of each other; as a group they cannot be changed continuously, but only by discrete steps corresponding to a range of possible materials. In a typical case the material parameter group is independent of the functional requirement parameters and the geometrical parameters.

For the conduct of design studies it is always possible and desirable to select independent geometrical parameters, which can subsequently be varied independently of each other. Often some geometrical parameters are limited in magnitude or restricted to standard sizes. Where this is the case, independent geometrical parameters should be chosen from those that are limited rather than from those which are not, if the choice exists.

In a typical design equation the group of geometrical parameters is often dependent on the specified functional requirement group and on the material parameter group; the equation takes the following form.

\[
A = f \left( \frac{\text{Functional} \text{ Requirement Parameters}}{\text{Material Parameters}}, \frac{\text{Geometrical Parameters}}{\text{Functional Parameters}} \right)
\]

The primary design equation \((P.D.E.)\) expresses the basic relationship of the quantity to be optimized. There will also be subsidiary design equations \((S.D.E.'s)\) relating functional requirements or significant undesirable effects, whether stated or implied. There will be limits on some of the quantities in these equations which will in turn be expressed by limit equations \((L.E.'s)\). The subsidiary design equations express the functional constraints and the limit equations the regional constraints.

A formal statement can now be made of the steps to be followed in obtaining the optimum design of a mechanical element. This statement is based on the work of R. C. Johnson and will be called therefore the
"Johnson method". There are two important cases to be considered, distinguished by Johnson as "normal specifications" and "redundant specifications".

Case (1): Normal specifications

(i) Make free-hand sketch of element, and select the independent geometrical parameters.

(ii) Decide on the quantity to be optimized, write the P.D.E., all S.D.E.'s and all L.E.'s.

(iii) Combine all S.D.E.'s with the P.D.E. by eliminating an unlimited and unspecified common parameter from the P.D.E. for each S.D.E. As far as possible geometrical parameters should be eliminated, since they can be varied independently of each other and since they can generally be varied continuously. In doing this, the P.D.E. will be so developed that it will consist only of specified values, independent parameters, and independent parameter groups.

(iv) Using the developed P.D.E. determine the variation of the optimum design quantity with respect to each independent parameter and independent parameter group. Considering these variations and the previously written limit equations determine the optimum values of each of these independent parameters and groups. This gives the final P.D.E.

(v) Select the optimum material on the basis of the material parameter group in the final P.D.E.

(vi) Determine the optimum values of any remaining geometrical parameters using the S.D.E.'s.

Case (2): Redundant Specifications.

Where redundant specifications exist it is not possible to combine the equations to include the effects of all S.D.E.'s and all L.E.'s in a single development of the P.D.E., i.e. step (iii) above is impossible. The general method of procedure is then modified as outlined below.

(i) As for (i) and (ii) in case (1).

(ii) Construct an ideal problem of normal specifications by temporarily ignoring one or more of the limitations or specifications.

(iii) As before, develop the P.D.E. for the ideal problem. The parameters whose limits or specified values were ignored in step (ii) will be eliminated from this developed P.D.E. - the "eliminated parameters". The P.D.E. will be so developed that within the confines of the ideal problem it will consist of parameters and groups of parameters which are independent of each other. Some of these parameters in the ideal developed P.D.E. - the "related parameters" - will be related to the eliminated parameters by the S.D.E.'s, the "relating equations".

(iv) From the ideal developed P.D.E. determine the variation of the optimum design quantity with respect to the independent parameters in that equation other than the related parameters, and hence the optimum values of these truly independent parameters.
(v) From the ideal developed P.D.E. determine the variation of the optimum design quantity with respect to the related parameters for all feasible designs in the ideal problem.

(vi) Now determine the variation of the eliminated parameters with respect to the related parameters, using the relating equations and imposing the limits on the eliminated parameters which were previously ignored.

(vii) By combining the results of steps (v) and (vi) determine the domain of variation of all feasible existing design solutions to the overall problem. Optimum values for both the related parameters and the eliminated parameters will then be found.

The advantage of the general method outlined is that it requires the study of functional relationships with respect to a minimum number of variables. Thus it is necessary to consider variations with respect to the related parameters only, instead of with respect to all the parameters in the original problem. This is a major simplification in most real design problems.


A simple shaft length l, diameter d, is subjected to a constant twisting movement $M_t$, and is to have a specified torsional rigidity $k$. The design is to be based on the maximum shear stress theory of failure, and a suitable factor of safety $N_y$ based on the yield strength has been selected. It is required to optimise the design for minimum height $W$ when the following materials are available.

<table>
<thead>
<tr>
<th>Material</th>
<th>Density $\text{lb/in}^3$ ((W))</th>
<th>Yield Strength (Tension) $10^3$ p.s.i. ((S_y))</th>
<th>Ultimate Strength (Tension) $10^3$ p.s.i. ((S_{\text{ult}}))</th>
<th>Modulus of Elasticity $E$ p.s.i. $10^6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel - AISI 4310</td>
<td>0.283</td>
<td>197</td>
<td>232</td>
<td>29</td>
</tr>
<tr>
<td>Titanium Alloy</td>
<td>0.163</td>
<td>130</td>
<td>150</td>
<td>16</td>
</tr>
<tr>
<td>Aluminium Alloy</td>
<td>0.101</td>
<td>72</td>
<td>82</td>
<td>10.4</td>
</tr>
<tr>
<td>Magnesium Alloy</td>
<td>0.067</td>
<td>28</td>
<td>40</td>
<td>6.5</td>
</tr>
<tr>
<td>Cast Phenolic</td>
<td>0.048</td>
<td>7.5</td>
<td>10</td>
<td>0.71</td>
</tr>
</tbody>
</table>

P.D.E. : $W = \frac{W \frac{\pi}{4} d^2}{l}$

S.D.E.'s : $k = \frac{\pi d^4}{32 \frac{G}{l}}$

$T_{\text{max}} = \frac{16 M_t}{\frac{\pi d^3}{l}}$

L.E. : $T_{\text{max}} \leq \frac{(S_{\text{ult}})}{2 N_y}$

This is a case of normal specifications and the S.D.E.'s can be
combined with the P.D.E. to eliminate the unlimited and unspecified geometrical parameters, \( l \) and \( d \).

\[ W = 2 \left( \frac{M_t^2}{k} \right) (wG) \left( \frac{1}{T_{\text{max}}} \right)^2 \]

Clearly \( W \) is minimized by having the independent parameter \( T_{\text{max}} \) at its highest value. Then

\[ W = 3 \left( \frac{M_t^2}{k} \right) (wG) \left( \frac{1}{S_{y}^2} \right) \]

This is the final P.D.E. showing groups of parameters. In this simple example there is no geometrical parameter group in the final P.D.E.

The second group on the right hand side is the material selection factor. Its values are:

- Steel AISI 4130: \(-0.875 \times 10^{-4}\)
- Titanium alloy: \(-0.579 \times 10^{-4}\)
- Aluminium alloy: \(-0.760 \times 10^{-4}\)
- Magnesium alloy: \(-1.54 \times 10^{-4}\)
- Cast Phenolic: \(-2.39 \times 10^{-4}\)

Of these materials, the titanium alloy would be selected. Once the values of the functional requirements have been specified the design can be completed. Thus if

\[ M_t = 10,000 \text{ lb. in.} \]
\[ (S_t)_y = 130,000 \text{ lb./in}^2. \]
\[ N_y = 2.5 \]

\[ d = \sqrt[3]{\frac{32 \times 10,000 \times 2.5}{W \times 130,000}} = 1.25 \text{ in.} \]

Example (2): Design of practical Torsion Shaft for Minimum Weight.

Consider a shaft that is to connect pure torque-transmitting elements in a machine as sketched in Fig. (3.14). It is to transmit a constant twisting moment \( M_t \) and have a torque gradient \( k \), both of which are specified for proper functioning of the system. The shaft is to be designed for minimum weight.

P.D.E.:

\[ W = \frac{w}{4} \pi d^2 l \]

S.D.E.'s:

\[ k = \frac{\pi d^4 G}{32 l} \]
\[ T_{\text{max}} = k_1 \frac{16 M_t}{\pi d^3} \]

L.E.'s: \( T_{\text{max}} \leq (S_t)_y / 2 N_y \)
\[ d \leq d_{\text{max}} \]
\[ L_{\text{min}} \leq l \leq L_{\text{max}} \]
The second S.D.E. is obtained by considering the significant stress, an implied undesirable effect; \( K_i \) is the largest stress increase factor in the shaft.

This is a case of redundant specifications. We proceed by first combining the S.D.E.'s with the P.D.E. to eliminate \( d \) and \( l \), and construct an ideal problem in which the limits on \( d \) and \( l \) are ignored temporarily.

\[
W = 2 \left( \frac{K_i^2}{K} \right) \left( \omega \frac{G}{T_{\text{max}}} \right)^2
\]

\( d \) and \( l \) are the eliminated parameters, \( T_{\text{max}} \) is the related parameter, and the relating equations are

\[
T_{\text{max}} = \frac{K_i}{16} \frac{M_t}{W_d^3}
\]

\[
T_{\text{max}} = \left( \frac{\pi G}{32 k \pi} \right)^{\frac{3}{2}} \left( \frac{16 M_t}{K} \right)^{\frac{1}{4}}
\]

At this stage, for any given material, \( T_{\text{max}} \), \( d \) and \( l \) are the only variables; \( M_t \) and \( k \) are specified, and \( K_i \) depends on the proportions of the keyway design.

Assume the following values

\[
M_t = 10,000 \text{ lb. / in.}
\]

\[
k = 50,000 \text{ lb. in. / rad.}
\]

\[
K_i = 2.0
\]

\[
N_y = 2.5
\]

In the ideal problem, \( W \) is clearly a minimum when \( T_{\text{max}} \) is at its upper value. If the variation of \( W \) with \( T_{\text{max}} \) is investigated for the same five materials as in example (1), the minimum values of \( W \) are found to be

<table>
<thead>
<tr>
<th>Material</th>
<th>Minimum Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel AISI 4130</td>
<td>35.1 lb.</td>
</tr>
<tr>
<td>Titanium alloy</td>
<td>24.1 lb.</td>
</tr>
<tr>
<td>Aluminium alloy</td>
<td>30.4 lb.</td>
</tr>
<tr>
<td>Magnesium alloy</td>
<td>82.2 lb.</td>
</tr>
<tr>
<td>Cast Phenolic</td>
<td>95.5 lb.</td>
</tr>
</tbody>
</table>

We now eliminate \( T_{\text{max}} \) from the developed P.D.E. of the ideal problem and reintroduce the previously ignored limited parameter \( d \). To study the variation of \( W \) with \( d \) it is convenient to use logarithmic scales, as shown in fig. (3.15), since

\[
W = \left( \frac{\pi^2}{128} \right) \left( \frac{w G}{k} \right) d^6.
\]

The implications of the limit equation on \( d \) are then apparent.

(i) \( d_{\text{max}} < 1.4" \), no feasible design exists.

(ii) \( 1.4" < d_{\text{max}} < 4.0" \), one or more of the materials can be used.

(iii) \( d_{\text{max}} > 4.0" \), all materials can be used.
For the purposes of illustration assume that \( d_{\text{max}} \) has been specified as 2\(^{\text{nd}}\) so that the first three materials can be used.

The variation of \( W \) with \( l \) can now be studied.

\[
W = \sqrt{2W} \left( \frac{W}{\sqrt{G}} \right) \left( \sqrt{k} \right) (l)^{3/2}
\]

This is shown in fig. (3.16) on logarithmic scales. Various types of ranges exist for feasible values of \( l \), for example:

(i) There are no feasible designs.

(ii) Depending on the limiting values of \( l \), the choice of material may be titanium alloy with \( T_{\text{max}} \) less than its upper limit, or aluminium alloy when \( T_{\text{max}} \) would be at its upper limit.

(iii) The choice lies between titanium alloy and steel neither of which is stressed to its upper limit.

From this study it is clear that optimum design for cases of redundant specifications has many interesting aspects. For any of the possible situations described the final optimum design would be uniquely determined after having considered the variation of \( W \) with \( l \). Thus after selection of the optimum material, the optimum geometry of the torsion shaft would be completely determined, using the original S.D.E.'s to make the necessary calculations.

It is instructive to make a general statement of the Johnson approach to the optimum design of mechanical elements. The two examples above show that this approach has certain distinctive features.

First, the material parameters are separated from the other variables to form their own groups in the design equation. In a great many cases this separation can be made without difficulty and we shall confine our attention to such cases. It should be remembered, however, that instances can arise in which the material parameters are connected to the other variables in a more complicated manner.

We shall identify the design variables (other than material variables) and any output variables occurring in the mathematical model of the element by the symbol \( x \). In mechanical design the values of some variables are unlimited and unspecified, and some are limited by regional constraints; these will be denoted \( x_u \) and \( x_l \) respectively. There is always at least one \( x_l \) limited by considerations of the strength of the element. This will be denoted \( x_{l1} \), and its upper limit, which can be regarded as a material property, \( m_u \), so that

\[
0 \leq x_{l1} \leq m_u
\]

Other material variables will be denoted by \( m_1, m_2 \ldots \).

The Johnson method has been developed to deal with optimization problems where there is one criterion function. If it is desired to introduce more than one criterion the design must be optimized under each criterion in turn, and the results compared in order to arrive at a compromise. Furthermore, it is assumed that the subsidiary design
equations which express functional constraints are in a form sufficiently simple and explicit to allow their combination with the primary design equation by a straightforward mathematical procedure. Each limit equation representing a regional constraint contains one variable \( x \) and is of the form

\[
1_i \leq x_{i1} \leq L_i
\]

The number of limit equations does not exceed the number of variables \( x \).

The two illustrative examples showed that the application of the Johnson method is greatly assisted by expressing all mathematical relations by exponential equations such as

\[
y = a x^b \quad (a, b \text{ constants})
\]

since this equation is represented by a straight line on a graph with logarithmic scales for the co-ordinates. It is important that wherever possible the mathematical model should be so constructed that it consists of equations of this type, graphical and tabular data being converted to this form too wherever possible.

The general statement of the Johnson method is then as follows.

**P.D.E.:**

\[
C = C (x_{u1}, \ldots, x_{t1}, \ldots, m_1 \ldots) \text{ to be optimum} \quad (3.20)
\]

**S.D.E.'s:**

\[
\alpha_1 (x_{u1}, \ldots, x_{l1}, \ldots, m_1 \ldots) = 0
\]

\[
\alpha_2 (x_{u1}, \ldots, x_{l1}, \ldots, m_1 \ldots) = 0
\]

\[ \ldots \]

and so on

**L.E.'s:**

\[
0 \leq x_{l1} \leq m_1
\]

\[
l_2 \leq x_{l2} \leq L_2
\]

\[ \ldots \]

and so on.

Suppose that the total number of variables \( x \) (\( x_u \)'s and \( x_l \)'s) is \( n \), and initially consider cases where there are \( (n - 1) \) subsidiary design equations. Three cases will be examined:

1. where the number of unlimited variables \( x_u \) is equal to \( (n - 1) \), the maximum possible;
2. where there are no unlimited variables;
3. where the number of unlimited variables is intermediate between zero and \( (n - 1) \).

**Case (1):** Number \( \alpha \) of \( x_u \)'s is \( n - 1 \); \( m = n - 1 \).

**P.D.E.:**

\[
C = C (x_{u1}, \ldots, x_{n-1}, x_{l1}, m_1 \ldots) \text{ to be optimum.}
\]

**S.D.E.'s:**

\[
\alpha_1 (x_{u1}, \ldots, x_{n-1}, x_{l1}, m_1 \ldots) = 0
\]

\[ \ldots \]

\[
\alpha_{n-1} (x_{u1}, \ldots, x_{n-1}, x_{l1}, m_1 \ldots) = 0
\]

**L.E.:**

\[
0 \leq x_{l1} \leq m_1
\]
The subsidiary design equations are solved for each $x_{u}$ in terms of $x_{L}$ and material variables. These solutions are then substituted in the primary design equation to give its developed form,

$$C = C (x_{L}, m_{1} \ldots)$$

This is the case of normal specifications where the criterion function has been developed so that one equation includes the effects of all the functional and regional constraints. The material parameter group in this equation can take on a finite number of discrete values according to the materials available. For each of these values the variation of $C$ with respect to $x_{L}$ is investigated, as shown in fig.(3.17). As a result of this step the material is selected and the value of $x_{L}$ found which brings $C$ to its optimum value. Fig.(3.17) has been drawn for a typical case where $C$ is to be a minimum and $x_{L}$ is then at its upper limit. The graphs of $C$ versus $x_{L}$ for the different materials are shown as straight lines on the assumption that it has been possible to express $C$ as an exponential function of $x_{L}$ and that logarithmic scales are used for the co-ordinate axes.

When $x_{L}$ and the material variables have been determined, the $(n-1)x_{u}$'s can be found from the $(n-1)$ subsidiary design equations, and the optimum design is completely established.

Case (2): Number of $x_{u}$'s = $n$; $m = n-1$.

P.D.E. : $C = C (x_{L}, x_{1} \ldots x_{n}, m_{1} \ldots)$ to be optimum

S.D.E.'s : $\alpha_{1} (x_{L}, x_{1} \ldots x_{n}, m_{1} \ldots) = 0$

$\alpha_{n-1} (x_{L}, x_{1} \ldots x_{n}, m_{1} \ldots) = 0$

L.E. 's : $0 \leq x_{L} \leq m_{L}$

$l_{2} \leq x_{L} \leq L_{2}$

$l_{n} \leq x_{L} \leq L_{n}$

This is a case of redundant specifications. The subsidiary design equations are solved for $(n-1)$ of the $x_{u}$'s in terms of the other $x_{u}$ and the material variables. The solutions so obtained are combined with the primary design equation to give a statement of the criterion function of the form

$$C = C (x_{L}, m_{1} \ldots)$$

There will be $n$ such equations, $i = 1, 2, \ldots n$. In other words there are $n$ design equations and $(n-1)$ of the variables $x_{L}$ are eliminated in turn in order to derive a set of equations which express the criterion function and include all the constraints on it.

$$C = C (x_{L}, m_{1} \ldots)$$

$$C = C (x_{L}, m_{1} \ldots)$$

$$C = C (x_{L}, m_{1} \ldots)$$

$C$ to be optimum
The group of material parameters in each of these equations can have a restricted range of values corresponding to the materials available. For each of these values $C$ is plotted against $x_i$, and then against each other $x_j$ in succession. (If exponential relations are used all plots are straight lines on logarithmic scales). As indicated in fig. (3.18) the optimum value of $C$ within the range of constraints can be found from inspection of the total plot, and the material is then selected. Once this has been done the value of each variable $x_i$ can be read off each graph of $C$ versus that $x_i$. The complete optimum design is established.

Case (3): Number of $x_i$'s between 0 and $n$; $m = n - 1$.

In this case the procedure is similar in principle to case (2) above. Suppose that there are $k$ $x_i$'s and $(n - k)$ $x_j$'s. Now there are $(n - 1)$ subsidiary design equations, and these are combined with the primary design equation in such a way that the $(n - k)$ $x_j$'s are eliminated, and then $(k - 1)$ $x_j$'s are eliminated in turn. The statement of the criterion function inclusive of all restraints is once again of the form

$$ C = C \left( x_1, m_1, \ldots \right) $$

such equations, $i = 1, 2, \ldots, k$. The optimum value of $C$ is found from an examination of the plots of $C$ versus $x_i$ in a similar manner to case (2) already discussed.

When the number of subsidiary design equations is less than $(n - 1)$, the problem becomes more complex since the developed primary design equations take the form

$$ C = C \left( x_1, x_2, \ldots, m_1, \ldots \right) $$

and the variation of $C$ with respect to the variables $x$ involves a consideration of spatial relationships. The simple two-dimensional plots as used in figs. (3.17) and (3.18) are no longer applicable. Nevertheless the Johnson method is valuable in the design of simple mechanical components as many instances fall into one of the three categories discussed above. They can then be readily handled by the design engineer with the aid of a slide-rule and logarithmic graph paper.

3.4.5. Conclusion.

The subject of optimum design has now been examined both for general cases and for specific mechanical elements. The methods of optimum design are another tool for the design engineer and he should appreciate its applications. These methods augment the traditional trial-and-error approach to design, but they do not relieve the designer of decisions concerning the nature of the system to be optimized. If the designer chooses an inherently poor system in the first place, optimization only helps him make the best of a bad situation.
During the last decade there has developed an increasing awareness in engineering organizations in industry and government of the tendency towards unreliability which exists in man-made devices. In addition to the problems of designing new products, establishing ways and means of making them or having them made, and then getting them on the market at a price the consumer will accept, there is a fourth problem: that of making the product reliable. As a consequence a new branch of engineering is making its appearance — "Reliability Engineering".

In 1961, for example, one large English automotive company set up a special Reliability section, and this has proved a highly successful innovation. This Reliability section co-operates closely with Engineering, Production, Inspection, and Service departments. Its duties include sending questionnaires to owners asking for frank comments on their vehicles, and asking dealers for detailed returns following their pre-delivery check-over of vehicles they have sold. The Reliability group also analyzes service department records and customers' letters and the information obtained is compared with works test reports and vehicle audits. This type of organization can be extremely valuable in securing quick corrective action by design or manufacturing departments.

However, the basic responsibility for product reliability rests squarely with the Engineering department. Reliability must be designed or developed into a product; it cannot be manufactured or built into it subsequently. In the past reliability has often been achieved by over-design leading to products which were solid and sturdy but expensive. Today products have to be more automatic, faster, smaller, and with the increasing complexity that these requirements bring reliability becomes a major problem. The position now often arises where it is more important to make a product right in the first place as repairs, when they can be made, are too costly.

The subject has received much impetus from military applications where vague references to weapons having "high reliability" were useless. Their reliability had to be measured, established and proved. Reliability can now be used as a quantitative as well as a qualitative concept; it is defined by the probability of successful performance. While the basic concepts of quantitative reliability grew out of failures of electronic components in military equipment, mechanical structures are also becoming more complex. They present more problems than electronic components because they are more difficult and costly to test, and as a result, reliability data are relatively scarce for mechanical equipment.

It is a matter of common observation that increasing the complexity of a product or system by adding more components to it greatly decreases its overall reliability. To take an example from weapons systems, in World War II on the eve of Dunkirk, a large quantity of arms
and ammunition had been collected in America and loaded on ships for transport to England. There was no time for secrecy and the German navy was well prepared to sink these ships. By coincidence, a new exploder mechanism had become available for their torpedoes. The submarines that were sent out to sink the ships from America were fitted with these more complex and supposedly more effective torpedoes. The submarines had no difficulty in finding the ships, but when the torpedoes were fired they passed harmlessly underneath. The reason for this failure was that the magnetic environment of the Atlantic was significantly different from that of the North Sea where the exploder mechanism had been successfully tested.

On the other hand, reliability testing and improvement of components should not be pushed to excessive lengths. A reliability programme should always be weighed against the specified use of the product, against time, and against money. Unnecessarily high reliability may be as bad, in terms of final results, as a low reliability. The German V2 rocket in World War II had 78% overall reliability. To achieve this very high figure, many V2's were fired in tests over a period of four years; the final reliable model came into use too late to be an effective military weapon.

The pace of technological advance also imposes problems of timing. In the transition from design and development to production the question arises as to how long a product can stay on the drawing board or in the laboratory without forfeiting its position on the market. Correct timing is extremely important for products of rapid obsolescence.

3.5.2. Definitions.

We now define "reliability" and the other concepts to be used in this discussion.

Reliability: the probability that a product will perform without failure a specific function under given conditions for a given period of time.

In everyday language, reliability denotes the dependability of a man or machine in performing a specific function. In engineering, the concept of reliability is assigned an exact and measurable meaning that is technically useful, and reliability studies are justified by the fact that they supply the means for relating the probability of failure-free operation with the expected use conditions.

Failure: the abrupt or gradual shift in some characteristic of an element such that the component containing the element is unable to perform its intended function.

Catastrophic failure: the abrupt shift in characteristic manifested by complete and sudden malfunction, e.g. shaft failure, motor burnout.

Drift failure: the gradual shift in characteristics so that eventually the desired function cannot be performed, e.g. progressive deterioration in performance parameter due to wear.
Infant mortality: failures during the first use of a product, birth defects. Such failures usually result from faulty manufacture and are weeded out by running-in tests. In consumer products these failures may occur within the guarantee period, and the products have then to be replaced; this may be a calculated risk in products designed for planned obsolescence.

Constant hazard mortality: accidental failures that are unpredictable, occurring by a chance combination of circumstances.

Wear-out: failure caused by ageing and fatigue, progressive reduction of product capability until its performance is degraded below the point of usefulness. Wear-out can be postponed by proper preventive maintenance.

Misapplication: failure caused by improper use. In what follows it is assumed that products have been correctly applied; this mode of failure which is directly caused by human error is excluded from consideration.

Classical mortality curve: this curve is shown in fig.(3.19) for a typical case. It consists of three phases, the first corresponding to infant mortality, the second to constant hazard failure, and the third to wear-out.

Failure curves: fig.(3.20) shows a typical failure curve for a product after the infant mortality failures have been eliminated by development testing. If a certain number of failures can be accepted in a given time, the dotted curve represents a product which has been over-designed. Fig.(3.20) shows the effect of preventive maintenance in which the periodic replacement of short-lived parts slows the rise of the failure-rate curve.

3.5.3. Factors Affecting Reliability.

The reliability of a device is only measured when it is put into service; its operational reliability is the product of its "inherent reliability" and its "use reliability".

\[
\text{Operational Reliability} = \text{Use Reliability} \times \text{Inherent Equipment Reliability}
\]

A newly manufactured product has an inherent reliability which depends on:

1. the selection and application of materials and processes;
2. the selection and application of components;
3. manufacturing techniques;
4. workmanship.

After a product has been manufactured various factors can subsequently affect its ultimate reliability. These can be grouped under the heading of "use reliability" and consist of:

1. effects of storage on the product;
2. effects of shipping and handling on the product;
3. the physical environment of its installation;
4. its operational suitability, the effectiveness of its human engineering;
(5) the capability of the operating and maintenance personnel;
(6) the operating and maintenance procedures;
(7) adequacy of auxiliary and supporting equipment.

Unless proper care is taken in the design, manufacture, distribution, installation, and operation of the product, any or all of these factors may act in a detrimental manner to reduce its operational reliability unnecessarily.

3.5.4. The Mathematics of Reliability.

A product is considered to be a system built up from a number of elements each with its own level of reliability. Block diagrams are used to represent the functional relationships between the various elements which contribute to overall performance of the product. Each block represents an element or group of elements and indicates what must or must not happen to it in order that the system performs its intended function. The block diagram plays an important role in reliability design analysis by pictorially describing the functions of the system. It is used as a form of mathematical model to relate the probability of success of the individual parts to the probability of success of the system. The combinations of elements most frequently encountered will now be discussed, the relevant block diagrams being shown in Fig. (3.21).

(1) Elements in Series.

Consider a system of n independent elements in series, having individual reliabilities $r_1, r_2, \ldots, r_n$. Failure of any one element causes failure of the system. The elements are independent, i.e. the probability of success of any one element is independent of whether or not another element, with which it is functionally associated, has failed.

Then the reliability of the system is

$$R = r_1 r_2 \ldots r_n = \prod_{i=1}^{n} r_i.$$  

In a system containing one hundred elements in series each unit would have to achieve an individual rating of 0.999 in order to attain an overall system reliability of 0.90 since

$$(0.999)^{100} = 0.90.$$  

Thus as components are added in series the system reliability decreases. The reliability of a system with components in series can only be improved by increasing the reliability of each component.

(2) Elements in Parallel.

Consider a system of n independent elements arranged in parallel. The probability of failure of a typical component of reliability $r_i$ is

$$f_i = 1 - r_i$$

The probability of failure of this system is

$$F = f_1 f_2 \ldots f_n.$$  

The reliability is

\[ R = 1 - F = 1 - (1 - r_1)(1 - r_2) \ldots (1 - r_n) \]

or \( R = 1 - \prod_{i=1}^{n} (1 - r_i) \quad (3.24) \)

One method of increasing reliability is to introduce parallel components into the system. If, for example, the reliabilities of two elements were 0.80 and 0.95, their combined reliability in series would be

\[ 0.80 \times 0.95 = 0.76 \]

If an additional element is introduced in parallel with the first one, then the overall reliability of the system is

\[ \left\{ 1 - (1 - 0.80)^2 \right\} \times 0.95 = 0.912 \]

an improvement of 12\%.

(3) System Standby.

Suppose that there are \( m \) systems in parallel, each system consisting of \( n \) elements in series, all elements having the same reliability. Then the overall reliability is

\[ R = 1 - (1 - r^n)^m \quad (3.25) \]

(4) Element Standby.

In the case of element standby suppose that there are \( m \) elements arranged in parallel, there being \( n \) sets of these parallel arrangements in series, as shown in fig. (3.21). If all elements have the same reliability, the reliability of the system is

\[ R = \left\{ 1 - (1 - r)^m \right\}^n \quad (3.26) \]

Unlike system standby, the element standby case approaches reasonable reliability with relatively few parallel or standby elements. For example, if \( r = 0.9 \), \( n = 3 \), \( n = 10 \), then system standby gives \( R_s = 0.723 \), whereas element standby gives \( R_s = 0.990 \).

The more series elements used in a system the lower its overall reliability. If it is desired to increase the reliability of a system by the method of element standby, the system is divided into as many elements as possible before paralleling.

(5) Effect of Switch Reliability.

Assume that each element used for paralleling has with it a sensing and switching device whose function is to switch the standby element into operation in the case of failure. This device has a finite reliability \( r_s \). The overall reliability for the case of element standby is then

\[ R = \left\{ 1 - (1 - r)(1 - r_s) \right\}^m \quad (3.27) \]

It is not profitable to carry sub-division for paralleling beyond the point where the element reliability \( r \) equals the switch reliability \( r_s \).
We now consider how the mathematics of probability can be applied to wear-out failures and constant hazard rate failures.

Wear-out failures tend to take a normal probability distribution about a mean life \( T \). The familiar form of the Gaussian bell-shaped curve is shown in fig.(3.22).

\[
y = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{(t - \bar{x})^2}{2\sigma^2}}
\]

where \( \bar{x} = \) mean life
\( \sigma = \) standard deviation in the distribution

The probability that a part will fail by a certain time is given by the area under the curve up to that time. The probability that the life of any one part will lie within a given standard deviation from the mean is

\[
\begin{align*}
\sigma & \quad 0.6827 \\
2\sigma & \quad 0.9545 \\
3\sigma & \quad 0.9973 \\
4\sigma & \quad 0.9999
\end{align*}
\]

With constant hazard rate failures, a random failure characteristic is observed in a population of components, and the failure probabilities are independent of both time of operation and of each other. The instantaneous survival rate then depends only on the number of components still operating.

Let \( S = \) number of elements surviving at time \( t \).
\( S_0 = \) original number of elements at time \( t = 0 \).

The instantaneous survival rate is proportional to the number of survivors.

\[
\frac{dS}{dt} = -\lambda S
\]

where \( \lambda = \) constant of proportionality, negative because \( S \) is decreasing with time.

\[
\begin{align*}
\int_s^{S_0} \frac{dS}{S} & = -\int_0^t \lambda \, dt \\
\frac{S}{S_0} & = e^{-\lambda t}
\end{align*}
\]

The L.H.S. is the fraction surviving at time \( t \) and is therefore equal to the reliability.

\[
R = e^{-\lambda t} \quad (3.28)
\]

The initial failure rate is \( -\lambda S_0 \). At time \( t \) the failure rate is \( \lambda S_0 (e^{-\lambda t}) \). The mean time to failure is \( T \) where
The variation of reliability with time is shown in fig. (3.23). This is the simplest form of relation being obtained by assuming $\lambda$ to be constant, i.e., by assuming that failures are equally likely to occur at any time in the life of the component. This is a reasonable assumption for electric components but may not be correct for mechanical components. Other more complicated distributions can be derived by allowing $\lambda$ to vary with time. An important one is the "Weibull" distribution used in the analysis of fatigue test data. This can be expressed in the form

$$R = e^{-\left(\frac{t}{\theta}\right)^\beta}$$

The exponential distribution obtained above is a special case with

$$\beta = 1$$
$$\Theta = \frac{1}{\lambda}$$

An example is now given of how a reliability calculation may be carried out in practice. Consider an electric motor having two brushes, two ball bearings, and a small fan on the shaft to draw outside air in around the field coils. Analysis of past failures shows that:

(a) the brushes have a sharply peaked wear-out failure characteristic with a mean time to failure of 1000 hours, with standard deviation 200 hours;

(b) failure of other electrical components (insulation breakdown etc.) is of the constant-hazard type for all practical purposes with a mean time to failure of 20,000 hours;

(c) failure of the bearings is of the wear-out type, centring on 1800 hours, with standard deviation of 600 hours;

(d) other unpredictable failures of the constant-hazard type — abrasive dust on the commutator or bearings — have a mean time to failure of 10,000 hours.

The question to be determined is what would be the cost of offering a 500-hour guarantee to buyers of this motor. It should be noted that both mechanical and electrical unpredictable failures have very long mean times relative to wear-out failures, but because of their even distribution in time, they will cause an annoyingly large number of motors to fail before wear-out failure takes over. If $R_a$, $R_b$, $R_c$, $R_d$ denote the reliabilities of the four items as shown in the block diagrams, fig. (3.24), the reliability of the motor is
\[ R = R_a^2 R_b R_c^2 R_d \]

and \[ R_b = e^{-\frac{500}{20,000}} = 0.975 \]

\[ R_d = e^{-\frac{500}{10,000}} = 0.950 \]

\( R_a \) and \( R_c \) can be found from statistical tables of normal distributions.

\[ R_a = 0.994 \]

\[ R_c = 0.985 \]

\[ \therefore R = 0.994^2 \times 0.975 \times 0.985^2 \times 0.950 \]

\[ \therefore R = 0.887 \]

If the manufacturer of this hypothetical motor wished to offer a 500 hour guarantee he would have to budget for repairing 11 out of 100 motors. Suppose that in order to improve reliability it is decided to shield the bearings to keep grease in and dust out. This might increase their wear-out life to 2500 hours mean time with the same standard deviation of 600 hours, and simultaneously double the mean time of unpredictable mechanical failures from 10,000 to 20,000 hours. Then at 500 hours

\[ R_c = 0.999 \]

\[ R_d = 0.975 \]

\[ \therefore R = 0.994^2 \times 0.975 \times 0.999^2 \times 0.975 \]

\[ \therefore R = 0.936 \]

The manufacturer would have to budget for repairing approximately 6 out of 100 motors.

Calculations of reliability during design can save much time and money in the successful development of complex products. Reliability analysis uncovers weak links and suggests redesign before full-scale field tests are possible.

3.5.5. Improvement of Reliability.

Much engineering design is an iterative developmental process, in which testing is a feedback device to guide redesign, re-examination and restatement of design objectives until an acceptable design is achieved. A design is conceived, manufactured and put into use. As results from the field reveal weaknesses in design, information is collected as a basis for specific corrective measures to be incorporated in subsequent redesigns. Many mature designs are the result of many such cycles of redesign based on the evaluation of data collected during field tests and service operations.

This historic approach to reliability improvement consists of a single information feedback loop embracing design, development, production, and field service, fig.(3.25a). A major weakness of this approach is the length of time taken to perfect the product. To cope with the rate of technological progress the "systems" approach to reliability improvement has been evolved, incorporating a multiple feedback. Fundamentally, this replaces many full redesign cycles by multiple predictions of the probable
results of many tentative design changes. Analysis and prediction based on design consultation and statistical techniques enable the equivalent of many redesign loops to be performed rapidly by computation.

When this process yields a design that can be predicted to have the highest possible operational reliability this design is frozen. Subsequently, quality control should prevent the manufacturing cycle from degrading the potential reliability inherent in the product. A final product evaluation phase following production establishes the success of the whole multiple control process before the product is released for use. In place of the single feedback loop characteristic of the historic approach, the multiple feedback approach employs several major and many secondary control loops, fig.(3.25b).

Consider now the case where it is required to modify a design to improve its reliability. There are three principal methods by which this may be done.

1. Increasing the margin between design strength and environmental stress.
2. Redundancy.
3. Replacement.

Each of these will be discussed in turn.

1 Increasing the Margin Between Design Strength and Environmental Stress.

Due to unavoidable variations in materials or in manufacturing techniques the design strength of a component will vary. We would expect the majority of a large number of similar components to have strengths near the average value for the group, while there would be smaller numbers with either relatively low or relatively high strengths. In fact the design strengths of these components would be distributed in a manner similar to the "normal" distribution of statistical theory. There would also be variations of a random nature in the environmental stress to which the components are subjected, leading again to a statistical distribution. This is illustrated in fig.(3.26) where it has been assumed that both distributions are normal. While this is a reasonable assumption it does not affect the form of the discussion which follows; the ensuing arguments are still valid in principle if the distributions are different from the normal.

To minimize the probability of failure the design strength of a component should be selected so that the average strength of the normal distribution of the inherent product strength is greater than the environmental stress and its distribution. Statistical evaluation of the variability of product strength compared with the expected variability of the environmental stress can provide an effective tool for design. However, at the present state of the art, serious limitations reduce the effectiveness of this technique. These limitations result from :-

(a) Insufficient data on product strengths due to
   (i) continuing changes and improvements in products;
   (ii) the high cost of testing programmes which are statistically valid;
   (iii) the inevitable phase lag and obsolescence of
past product data in contrast to the advanced products currently employed in new designs.

(b) Poor definition of environmental stress distributions due to lack of data.

The probability of failure of the design is indicated by the overlap of these two distributions, as shown in fig. (3.26). Several solutions are available to minimise the chance of failure by increasing the separation of the distributions so that any overlap is reduced or eliminated:

(a) Increase of the design strength and factor of safety. This may involve severe penalties in weight, size, and cost.

(b) Reduction of the variance of the strength distribution by tighter control of the product. Consideration has then to be given to additional costs of closely controlling manufacturing, handling, and storage.

(c) Reduction of the effect of environmental stress on the design by decreasing the average of the stress distribution. This can be accomplished by insulation or isolation, but may be costly and has the disadvantage that additional complexity is introduced so that there are more possible failure mechanisms.

However, since a major consideration in design for reliability is accurate knowledge of the environmental stresses and the design strengths and their inter-relationships, and since often this knowledge is limited, insulation or isolation techniques may be used to provide added assurance for the design, and increase its service life. The type of protection employed depends on whether the detrimental stresses are transient or steady. Thus, steady mechanical stress might require the addition of a vibration mounting, while transient stress might require both vibration and shock mountings. Steady thermal stress might require insulation or shielding plus heating or cooling, while transient thermal stress could omit the latter or substitute a thermal capacitor. Steady electrical stress might require insulation, shielding, or filters, while transient stress protection could be provided by fuses or circuit-breakers. Whether or not protection is the answer depends on the product; protective devices may be too bulky, too heavy, or too costly. Usually, however, it is easier or cheaper to protect components than to develop new components that will tolerate the adverse environments.

(2) Redundancy.

We have seen how the addition of parallel or "redundant" elements can improve the reliability of a system. Standby systems are, of course, common practice, for example, standby boiler feed pumps and auxiliary generator sets; the standby unit takes over when the original system fails, being switched in either automatically or manually. In electrical systems there may be series redundancy instead of parallel-duplicated elements in order to guarantee fail-safe operation.

There are two main types of redundancy:

(a) Standby: a component or system which replaces another only when the first one fails. This is particularly suitable when the primary cause of failure is wear-out, but requires a highly reliable sensing and switching device since the reliability of a standby redundant system is
affected by that of the switching or selection device.

(b) Full-time: all redundant components or systems operate at the same time. This is particularly useful when chance failures may be expected, for example, a four-engined aircraft capable of take-off on three engines and flight on two.

(3) Replacement.

If some components have wear lives less than that of the complete system, means must be found for extending the period of their effective operation. One common expedient is to carry a sufficient stock of spare components for replacing sequentially those which fail during the working life of the system. If reliability is to be achieved through replacement of short-lived components, consideration must then be given to such questions as - optimal plans for intermittent use of components, number of different varieties of components to be stored and brought into service.

In general, combinations of the various techniques discussed may be advantageously used in design for high reliability. Their limitations must be borne in mind and, where necessary, compromises made.

3.5.6. Conclusion.

The methods of reliability analysis which have been examined here are an essential tool for the designer of complex engineering products and an appreciation of these concepts should be part of the mental equipment of all engineering designers.

In conclusion let us turn to the wider question of the recognition of the need for product reliability in an engineering organization. An organization manufacturing complex engineering products must have an integrated reliability programme, with clear responsibilities for the following functions.

(1) To establish product reliability in the design.
(2) To verify the reliability through a sound test programme.
(3) To assure reliability through properly engineered manufacturing processes and a tight quality control programme.
(4) To sustain reliability by a well-developed product support activity.
(5) To improve reliability through a feedback system that is universal throughout the programme.
4.1. INTRODUCTION

An engineering design moves progressively from the abstract to the concrete. It starts from some goal perhaps only dimly perceived or partially understood; it proceeds through the creation or selection of a specific design concept for meeting that goal to the detailed working out of this concept and the preparation of manufacturing instructions. In previous chapters we have considered the planning of products to meet human needs, the creation of design concepts, the role of communications, and discussed the major tools for the analysis and development of design concepts in engineering.

Throughout there has been an overlapping of purely engineering and purely economic considerations. In the early stages engineering predominates but economics can never be wholly absent. As a design progresses economic factors begin to weigh more heavily as more people and resources are brought to bear on the problem; the closer we are to preparing manufacturing instructions, the greater is the influence on the design of the subsequent processes of manufacture and distribution.

It is the purpose of this chapter to examine the influence of economic factors on design, particularly during the later stages of a project after the design concept has been chosen and when its detailed expression is being developed. Major factors which play a part in achieving an economical design are:

1. Design policy
2. Use of standards
3. Selection of manufacturing tolerances
4. Application of value analysis
5. Application of special cost control programmes.

Each of these will be discussed with the aim of making useful general comments, but without delving into details concerning particular industries or processes, subjects on which there is a vast quantity of data not capable of generalization. Some of this discussion will extend beyond the immediate responsibilities of a design department, but the designer should nevertheless understand clearly how they can assist him to produce a more economical design.

To make a general statement of the economics of a design, consider a product consisting of a hierarchy of n components arranged in m sub-assemblies.
Let $C_i = \text{cost of typical component}$

$A_i = \text{cost of assembling a group of components into a typical sub-assembly}$

$A = \text{cost of assembling sub-assemblies into product (including packing and other finishing operations)}$

$D = \text{cost of development, spread over } x \text{ products.}$

$G = \text{unit cost of servicing product in guarantee period.}$

Then the cost of the product to the manufacturer is

$$C = \sum_{i=1}^{n} C_i + \sum_{i=1}^{m} A_i + A + \frac{D}{x} + G \quad (4.1)$$

Presumably the selling price is

$$S = pC \quad \text{where } \quad p > 1 \quad (4.2)$$

The values of $S$ and $p$ will be influenced by external conditions, such as the degree of competition and the value the community assigns to the product.

### 4.2 DESIGN POLICY

#### 4.2.1 General

The management of an engineering company should have clear-cut policies concerning range of products, their design and quality, the periodicity of design improvements, and on special subjects such as tariffs and imports. It is desirable that information on such policies should be widely disseminated "down the line" so that the design staff can appreciate their own work in relation to the overall position of the company, and to ensure that their work is in fact in accordance with company policy, for example, to ensure that products are not over-designed.

Policies are framed in response to the trading situation of the firm. One firm may try to maintain its competitive advantage by low prices combined with adequate functional performance, whereas another firm may endeavour to improve the quality and lengthen the life of its products without increasing their price. The comment has been made that, in America, the engineering industry makes a very careful assessment of the standard of quality required for a product. Where the job requires high quality and precision these are provided; but the non-essential use of high-grade materials and workmanship is regarded not as a virtue but as a vice leading to wasted effort and lowered productivity. This attitude is summed up in the phrase, "we don't paint the underside". The standard of quality of a product will be influenced by the degree of competition and the expected rate of obsolescence. In some industries, notably consumer goods, the pace of industrial development coupled with strong competition entails very short redesign cycles, and this imposes a heavy load on engineering and manufacturing departments.
4.2.2. Variety Control.

One of the responsibilities of engineering management is the formulation of a policy on the control of variety in design in order that unnecessary and unprofitable work be eliminated. A properly planned programme of variety control can bring substantial benefits to productivity, since one of the aims of good design is to provide maximum variety of products from the minimum variety of components and parts using the minimum variety of primary tools and materials. The principles of variety control can be applied at several levels in design: to complete products, to the components and parts from which they are assembled, and to the materials and methods used in their manufacture.

It often happens that the number of end products made by a company tends to proliferate without adequate planning, as different sections within the company promote their own bright ideas. Control of product variety then takes the form of reducing the number of products by eliminating those which are unprofitable or which are not contributing their share to the company's business. To do this requires information, product by product, of sales income, stock levels, and manufacturing costs, and, of course, a system of accounting which ensures that costs of production are truly reflected in the selling prices of the different products. The profitability of each product is analyzed, and wasteful diversification restrained. Variety in many consumer products has reached epidemic proportions. In Australia today there are over one hundred and eighty different washing machines on the market. Whether this excessive variety represents efficient use of the nation's resources must be doubted, but there is little that can be done to rectify this in a democratic society where the citizen's freedom of choice may not be arbitrarily restricted by the state. However, it can be agreed that a designer should resist any trivial or unnecessary modifications to a product.

In many industries while end-product variety has to be maintained to satisfy the needs of the customer, there is still ample scope for variety control to be used in the simplification and standardization of components, materials and tools. For instance, where an organization manufactures a range of functionally similar products, there must be some potential interchangeability amongst the sub-assemblies, components and parts used. Modular aspects arising from the common function of the products can then be exploited. For example, refrigerators tend to have similar heights and depths so that they can pass through normal doorways. A range of refrigerators of varying cubic capacities would be designed by combining the same front and rear panels with side panels of varying depths, rather than by varying height or width. As another example consider a range of centrifugal pumps where each product consists of a pumping device and a bearing housing which supports its rotor. A small number of bearing housings can be used in the design of a large number of hydraulic pumps. Furthermore, the design of the components of all end-products can often be based on the same materials as for any single product. Awareness of this leads to
advantages in economical purchasing and simplified stock control and ordering.

To control the proliferation of variety in design, particularly with respect to parts and materials, the most effective weapon is a coding system whereby each item is identified and classified according to its fundamental nature, rather than according to conventional nomenclature, proprietary name, or function which may be difficult to define. Too often a new part is designed because the task of locating a similar existing part is arduous, time-consuming and ineffectual. The functions of a good classification system are:

1. to make it possible to find an existing item or to ascertain that a particular item does not exist;
2. to find all the items capable of satisfying a given need;
3. to find all the needs a given item can satisfy;
4. to ensure that there is one place and one place only for recording all existing items and future additions.

Once a system has been established duplications are revealed and removed, thus reducing variety. Proposals for the creation of new items are critically examined to see whether a similar item already exists or whether the proposed item could be made to fill the function of a number of items already in existence. Items can be assembled in one place and drawings compared to see whether one part would serve the purpose, or if not, whether a new part can be designed to serve the purpose of some of the old ones.

A classification system is a tool of design management, a means for controlling excessive variety, introducing standardization, and promoting rational design.

4.3. CONTROL OF COSTS DURING DESIGN

4.3.1. Standardization

Standardization may be defined as the process of formulating and applying rules for an orderly approach to a specific activity for the benefit and with the co-operation of all concerned, in particular for the promotion of optimum overall economy taking due account of functional conditions and safety requirements. An engineering standard is a record of the systematic arrangement of technical data and engineering judgment so that an engineering enterprise can make more effective use of the talent applied to the job. Standardization covers a wide range of subjects such as: codes of practice, draughting methods, material specifications, process and finish specifications, tolerances, components and parts, tooling, test procedures, packing and shipping, quality, safety.

Standards are an essential part of the language of commerce and industry, the means by which the consumer describes what he wants and receives assurances of suitability and quality from the manufacturer. Properly used and periodically revised standards do not inhibit design but contribute largely to its effectiveness. The Anglo-American Product-
Council Report on "Design for Production" recommended that a separate standards department should be set up as an advisory or service function, even in the smallest engineering firms. In fact most large firms are now well aware of the advantages of standardization and have established special departments to promote this within the company. Nevertheless, it is surprising how many small firms, who collectively contribute a large share of the nation's economy, are still unaware of the standards which are available to them and of the extent to which they could help them, both in lowering costs and in stimulating their business.

The objects of a standards department in an engineering company may be summarized as follows.

(1) To promote the development and maintenance of sound engineering and manufacturing standards and practices throughout the company, so that maximum interchangeability, simplification of parts and practices, economy of manufacture, improvement of quality and consistency of appearance are secured for all types of the company's equipment.

(2) To co-operate in the development of appropriate industry standards, codes and ordinances which pertain to the manufacture, sale, installation and use of the company's products.

(3) To determine questions of policy and promote uniformity of procedure in obtaining approvals of equipment where required by code-enforcing authorities.

(4) To publish and distribute within the company "company standards" and information relevant to the activities outlined above.

It will be seen that standardization is closely allied to variety control; the two often overlap and are implemented together. Standardization is essentially a technical activity, whereas variety control includes broader considerations of commercial policy, particularly when attention is being paid to controlling the number of varieties of products or components.

4.3.2. Tolerances.

No manufacturing operation can be carried out with absolute precision, there is always some error between the exact dimensions chosen by the designer and those actually obtained in the manufacture of the product and its components. The designer therefore specifies tolerances in order to prescribe the amount of error that can be accepted in the dimensions of a part without adversely affecting its compatibility with other parts or the functioning of the product. Tolerances may also be specified for overall dimensions of the completed product to ensure compatibility with its environment.

The tolerances and surface finish specified for a part by a designer have a marked bearing on the cost of its manufacture, and hence on the economics of the design. In general, the looser the tolerances and the coarser the surface finish permitted, the lower the costs of manufacture and inspection. On the other hand, excessively loose tolerances may lead to problems in assembly and performance of the
product. These factors will be borne in mind by the designer when he
prescribes tolerances and surface finish. In setting these limits, he
will be chiefly influenced by the function the part is to perform, but
he will also have to consider the method by which the part is to be made
since most processes have a characteristic range of accuracy to which they
are suited. In what follows discussion will mainly be confined to
machining, but similar arguments can be used with other manufacturing
processes although often only limited data is available for them.

There is a definite relationship between grades of tolerances
and the methods of manufacture which can be used to produce them. This
relationship is reasonably well defined, although it does depend on proper
maintenance of tools and inspection equipment, and the level of quality may
vary in different applications. An engineering organization should select
the classes of fit for mating parts suitable for its range of products,
using the appropriate British standard, B.S.1916 : 1953, to do this.
It should then standardize on a preferred range of limits and fits corre­
sponding to the most common applications found in its products. Fig.(4.1)
shows tolerance grades related to machining processes, and lists a selection
of fits suitable for general engineering purposes. In this way the
specification of tolerances and surface finish can be made a straight­
forward procedure by a design group who maintain and use their own standards
in conjunction with recognized standards such as B.S. 1916. Nevertheless,
it is unfortunately true to say that the use of such standards is not as
widespread as it should be.

The tolerancing of a dimension which itself depends on a number
of other dimensions all with their own tolerances raises some interesting
problems. It is a simple matter to estimate the maximum cumulative effect
arising from the component tolerances by assuming that cases can arise where
these tolerances are at their extreme limits. If the tolerance on the
overall dimension is small this approach may lead to component tolerances
which are impractically small. However, the probability that all these
extremes will occur together is very low, and in fact probability theory
can be applied to obtain looser component tolerances consistent with an
overall dimension which is most unlikely to be outside the specified limits.

In general, a number of similar parts produced by the one process
will have a range of dimensions which tend to be distributed about some
mean value. In machining operations it is found that the frequency
distribution lies close to a normal curve; a typical situation is illus­
trated in fig.(4.2.) where it is assumed that the cutting tool has been
initially set so that the maximum margin is allowed for tool wear within
the tolerance zone. The total frequency distribution is then of a quasi­
normal form as shown.

On the assumption that all dimensions have a normal or quasi­
normal distribution it is possible from statistical theory to predict the
probable maximum deviation P from the mean of the sum of the individual
dimensions. Consider a simple case where there are n dimensions each
subject to a tolerance \( t \), production being in medium or large quantities with tolerances greater than or equal to those in IT 6, B.S. 1916. The result is obtained

\[
P = \pm \frac{t}{\sqrt{n}} S
\]

(4.3)

where \( S = \frac{1}{2} n t \), the sum of the half-tolerances, or permissible maximum deviations of the individual dimensions.

Thus if \( n = 6 \), \( t = 0.020" \) (\( \frac{1}{2} t = \pm 0.010" \))

\[
S = 0.060"
\]

and

\[
P = \pm \frac{1.4}{\sqrt{6}} \times 0.060
\]

\[
\therefore P = \pm 0.034".
\]

In cases such as this and in others of greater complexity (where the t's vary and the frequency distributions depart from the normal), the probable maximum deviation of the sum of a series of dimensions is found to be significantly less than the permissible maximum deviation. Application of probability theory then enables the designer to relax the individual tolerances with the knowledge that the overall dimension will be within the limits required in all but an extremely small number of cases. In special circumstances the conditions of design may be so stringent that even this very small number cannot be accepted. However, in the great majority of designs the methods briefly outlined here offer a means by which the engineer can improve the producibility of his design. Published work on the use of probability theory has so far been confined to machined dimensions, but experience has shown that it may be used successfully in the field of pressed metal components. Further research would be desirable to confirm extension of the theory to other applications in engineering industries.

4.3.3. Value Analysis.

The techniques of value analysis have been developed as an additional tool for the designer in his efforts to reduce costs. They are especially applicable to the design of products and components which are to be manufactured in large quantities. The purpose of value analysis is the efficient identification of unnecessary cost, that is cost which provides neither quality nor performance nor appearance, nor any other feature to attract the consumer.

It was observed in Chapter 1 how the value of a product alters as it moves around the cycle of production, distribution and consumption. Broadly speaking, the analysis of the value of a product to the consumer is based on considering its "use value" and its "esteem value"; the use value is the lowest cost of providing for the reliable performance of a function, and the esteem value the lowest cost of providing for appearance, attractiveness, and other features which the customer wants but which are not essential to the performance of the product. These minimum costs have to be found by comparison with other similar products on the market or with other products which perform similar functions.
The basic steps in reducing the costs of engineering products by this method are: (1) identify each function of the product and of its components; (2) evaluate the functions to determine their value in pounds, shillings and pence; (3) develop alternative, lower cost designs.

An oft-quoted example of how value analysis may be applied comes from America and deals with the design of fuel tanks in U.S. Navy landing craft. The original design called for a special alloy tank costing $520. In this instance the function to be performed by the product can be readily identified: to contain 200 U.S. gallons of petrol in the landing craft throughout its working life. To evaluate this function the question is asked - what is the appropriate cost for housing 200 gallons of petrol. Four standard 50 gallon drums could be used, costing $25. Some environmental treatment would be required, also some extra connections, so add $25 to arrive at a tentative figure of $50 for the petrol-containing function.

It is immediately clear that the special alloy tank is too expensive. An alternative design was then developed based on the suggestions of this value analysis; its cost was $80, and as 1,000 tanks were required the total saving to the American taxpayer was considerable.

Value analysis tries to identify each element of function of a product provided by each element of its cost, to determine the contribution to function furnished by each activity in manufacturing which adds cost. The aim is to remove from the design of the product all features which add cost but do not contribute proportionately to its value to the consumer.

4.3.4. Programmes for Cost Control.

Engineering management should adopt specific measures to assist the control and reduction of costs at the design stage. Because of the wide field of knowledge covered by common production methods it is difficult if not impossible for any one person to keep at his fingertips all the detailed data necessary for design at minimum production cost. It is therefore often desirable to organize specific engineering programmes to this end. Cost control programmes take various forms depending on the size of the company, its management, the complexity of its products and the calibre of its design engineers. They can be very effective in fields of non-repetitive, small-lot production as well as in the repetitive production of fairly standardized components. For example, the total cost of a large engineering design project is normally estimated from quite broad assumptions. If the estimate is considered satisfactory, the project is then broken down into parts for detailed design, leading on to detailed manufacturing plans. If the cost of each part of the project could be budgeted before detailed work started and checked again after design and before manufacture, there would be opportunity for over-elaborate designs to be pruned before it is too late to make any changes and before a loss is inevitable. However, this approach involves tedious procedures, the estimates are difficult to make, extra staff are needed, and the argument is often advanced that it inhibits good design. The result is that this type of systematic approach is all too often not used. As an example of
what can be done, an English firm manufacturing heavy steel works plant recently introduced a new department into their design office specifically for this cost control work, and found that they saved £100,000 on one contract alone.

Methods used for control of costs during design depend on the size of the company or engineering organization.

(1) Small to Medium-size Companies.

In small and medium-size companies the problem of designing for production can be made the responsibility of a member of the engineering department sometimes known as "methods engineer", "product methods engineer", or "production-design consultant". The larger the company the more product methods engineers there will be on its staff.

The products methods engineer provides the link between design and production. It is his duty to collaborate closely with the responsible design engineer at all stages of design. To co-ordinate design and manufacture he may prepare a preliminary draft of manufacturing instructions when the design is first laid out. Costs can then be forecast, and from such information support for authority to make extended design investigations into more economical methods can be obtained. Constant surveillance by these means makes it possible to avoid any factors tending to direct a design into more costly channels. In addition, the common sequence of design changes to suit manufacturing facilities which are reflected in expensive tooling changes and hidden costs are eliminated.

(2) Medium to Large Companies.

In medium to large organizations the design committee review plan has many merits, and is a democratic and effective method of controlling design costs. The committee checks a design at critical stages of its development, and recommends changes that will improve it. Fig. (4.3) illustrates how the work of the committee is integrated with the evolution of a design in a typical case.

Based on the concept that designs and recommendations are more acceptable to members who participate in their formulation, the committee is composed of representatives from all departments affected by the decisions made and policies adopted. The departments represented would usually include: engineering, production planning, tool design, manufacturing, purchasing, inspection, service, and sales.

The mode of operation of a design review committee should be carefully planned, regular meetings are necessary along with good but not excessive records and proper follow-up. The exact scope of the committee must be established to keep the operation successful and within practical bounds. All new designs or redesigns are brought before the committee members for approval or recommendations. Once the design is passed, the common problems of engineering "errors" or changes and production difficulties should be largely eliminated.
In large engineering departments with many integrated basic divisions, the method of setting up a special design-cost group has worked very successfully. Because of pressure for output, need for concentrating on creative design, and the increasingly critical time span on engineering projects, the time necessary to make adequate cost studies is often not available. However, thorough design evaluations are a "must" for results and the responsibility is therefore assigned to the design-cost group. Such a group functioning in a consulting capacity can devote all its time to this activity and operate in an unbiased manner.

Generally, a design-cost group collaborates with the design and development sections of an engineering department which report directly to the chief engineer. Its duties are twofold. One unit of the group covers new designs providing on-the-spot information on design costs. The second unit covers development and works up basic design-cost data and standards on design for production. The second unit collaborates with the first in the preparation of detailed comparative cost analyses to minimize detail duties and allow sufficient freedom for contacts with members of the design staff. Fig. (4.4) shows how the organization of design-cost control functions in a large American aircraft company.

The aim of all design-cost control programmes is the evolution of production-conscious designers, who make full use of the company's resources on production methods and costs to achieve the most economical design.
5.1. GENERAL

We have seen that engineering design begins with an awareness of a human want or need which is to be satisfied. This need is usually expressed in general terms and the engineer's first task is to develop quantitative specifications of the problem to determine what has to be done to achieve the goal. He then creates concepts which are possible solutions of the problem; the higher the innovative content of the project the greater the demand on the engineer's inventive and creative powers at this stage. The various design concepts are analyzed, evaluated and decisions made regarding their feasibility and relative worth. This continues until sufficient information is obtained to enable the best design concept to be selected; it is then developed into a detailed statement of the solution to the problem, giving specific instructions for the manufacture or construction of the product. One can summarize the major steps in the evolution of an engineering design in the following manner.

(1) Recognition of goal.
(2) Specification of task for designer.
(3) Creation of design concepts.
(4) Analysis and evaluation of design concepts.
(5) Development of detailed solution.
(6) Manufacture and sale of product.

As has been pointed out, these steps need not proceed in direct chronological sequence. Often new information comes to light during one step which necessitates the reworking of one or more of those preceding it; unpredictable associations occur between the different steps so that many iterations may be required. For example, having specified the job to be performed by the designer and created and analyzed several concepts, we might decide that the goal sought is not the proper one and go back to its original statement and alter it.

In this thesis the nature of engineering design was studied in detail in the first part of Chapter 2. Later sections of this chapter dealt with the first steps in design: - product planning, the initial specification of the problem for the designer of engineering products; and creativity, the means by which he arrives at possible solutions. Communications were then discussed, and the input of information to the designer and the output from him examined.

In step (4) - the analysis and evaluation of design concepts - there are some general methods of wide importance in engineering mainly based on the use of mathematics, and these were discussed in Chapter 3. Engineering factors tend to predominate at this stage, but in step (5),
as the detailed description of the product evolves, economic factors become more significant, and it is appropriate therefore to make a general appreciation of them and examine the question of controlling costs in design. This was done in Chapter 4. The project culminates in the detailed specification of the final product by means of drawings, parts lists, specifications, special instructions, and so on. The subsequent processes of manufacture and distribution must influence product design. However, the techniques and characteristics of different industries and processes vary so widely and there is such a mass of information on these subjects which is not capable of generalization that little space is given to them here. This is not because of lack of recognition of their importance but because such specialized topics fall outside the intended scope of the thesis.

Indeed, the design department exerts a controlling influence on the productivity and efficiency of operation of the whole organization of which it is part. Design engineering has a potent influence on economy of production by stimulating sales and by making it possible to keep costs to a minimum.

5.2. THE DESIGN ENGINEER

To conclude, we return to the design engineer and consider the qualities and abilities which distinguish him from his fellows. As we have seen he must possess a wide body of knowledge, together with certain skills, attitudes and attributes. Many of these can be learnt in courses of formal instruction, and to some extent all can be acquired or developed on the job. Their relative usefulness will depend on the type of product being designed, its innovational content, and the consumer for whom it is intended.

The knowledge required by a design engineer has been classified in Chapter 2. The individual designer should identify and select those categories which are of greatest value to his work and see that this information is made available to him in an efficient manner.

A designer must possess certain skills. Skill in using the analytical tools provided by mathematics and the engineering sciences is important and will become more so as man works on the frontiers of engineering. Skills in communication are also necessary; the designer must be able to present his ideas to others in a convincing manner, either verbally or by means of sketches and drawings. While these skills can usually be acquired without much difficulty, there is in addition another skill which is more difficult to acquire and which may be part of a person's mental resources. This is the skill in analyzing problem situations to sort out relevant data and discard the false and irrelevant, in order to formulate an idealised model which represents the real situation in a conceptual form amenable to attack by theoretical analysis.

In his approach to his work the design engineer expresses certain attitudes and qualities of mind. In the discussion on creativity in Chapter 2 we distinguished the following: intellectual integrity, driving
curiosity, constructive discontent with the status quo, courage and persistence, willingness to take risks and accept responsibility, power of concentration, flexibility of mind. Of course, no one man can be expected to possess all these qualities in the highest degree, yet each must be present and play its part in forming the character of the good designer.

Finally, we recognize that there are attributes such as creative power and judgment which are essential to the designer, and the creative features of engineering design have been emphasised in this thesis. Many people would say that these qualities are inherent in personality. However, there is evidence to suggest that not only may they be repressed by an education that is too formal and confined, but also that they may be developed by special training, witness the fact that several famous American engineering companies have instituted training schemes in creative engineering. Allied to creativeness is another attribute which has marked the work of all great engineering designers, and which may be called an engineering aesthetic sense. It is this sense which gives a designer an innate skill in the proportioning of components, in making acceptable compromises between the many conflicting claims with which he is faced. It is this sense which enables him to extract a formal unity from a diversity of components and separate interests. One of the great engineering designers, Sir Henry Royce, was largely self taught but had this gift of engineering aesthetics. He designed his engines with little or no knowledge of the theory of elasticity, leaving it to others to carry out detailed stress analyses which usually confirmed his original design.

One of Britain's leading designers of special purpose machinery, Mr. T. A. Kestell, recently stated that it took twenty years to produce a first-class design engineer. Clearly it does not take a designer twenty years to acquire the knowledge and skills in mathematics and communications that he requires in the exercise of his profession. However, over a long period of time he would have had to use his creative powers in tackling many problems and would have built up a considerable store of experience. Moreover, his skill in proportioning his designs and in imposing a unified purpose on them could then be expected to be highly developed. One can interpret Mr. Kestell's observation by saying that there are many intangibles in engineering design where judgment based on prior experience plays a vital role in decision-making. The development of this power of judgment can only come after prolonged exposure to situations requiring its exercise.

One must beware of too sweeping generalizations. In one case known to the author it was possible to compare the work of two designers, both honours graduates of European universities, one with twenty years' experience, the other with eight, both working on the design of similar engineering products of fairly low innovational content. The designs of the younger man were much superior, not because of greater creative ability or aesthetic sense but because of better knowledge and appreciation of the particular engineering science on which the design of the product was based. Again, in one of the first problems he met as a designer the author could think of only one not very satisfactory answer. His immediate superior,
was also stumped, but another more senior member of the design staff put forward a very ingenious idea which formed the basis of the eventual solution. This example shows not so much the superior creative powers of the senior man but his wider experience in that his suggestion was directly based on the results of work he had carried out on another similar problem.

A point often overlooked is that it is always desirable to give a designer a wide variety of problems to deal with, so that his creative ability is fully exercised and there is no tendency to staleness. This is the major advantage of a consulting organization: a design staff in one firm are engaged on a limited range of problems, and may therefore be too inclined to think along stereotyped lines. An engineering company should do everything in its power to promote the mental elasticity of its designers. Thus, after a few years designers in heavy engineering are usually unfitted for light engineering and vice versa. In support of this statement one can point to the case of the steam turbine designers who designed a gas turbine plant for a ship, only to find that the product was so heavy and massive as to be useless. The design then had to be taken over by an aircraft engineering firm who were used to thinking in terms of maximizing power-to-weight ratios.

In conclusion it is hoped that these comments have provided some further insight into engineering design and the work of the design engineer. By and large designers are inarticulate about their work, and it was this silence which prompted the writing of the thesis in an endeavour to set out the fundamentals of the subject.
Because the subject of Engineering Design is so very wide this bibliography is not exhaustive. Only references which the author feels to be of particular relevance or importance to the thesis are listed.

Chapter 2


Chapter 3


Chapter 4

International Organization for Standardization. ISO/STACO No. 239, Aims of Standardization.

British Standards Institution, B. S. 1916, "Limits and Fits for Engineering".


FIG 1.1. THE PRODUCTION-CONSUMPTION CYCLE.
**Legend:**
- Circles denote primary sources of information.
- Rectangles denote stages in the progress of the design.

**Fig 2.1. The Structure of a Design Project.**

Phase (I) - The Feasibility Study.

(After Asimow.)
FIG 2.1. THE STRUCTURE OF A DESIGN PROJECT.
PHASE (2) - PRELIMINARY DESIGN.
(AFTER ASIMOW).
FIG 2.1. THE STRUCTURE OF A DESIGN PROJECT.
PHASE (3) - DETAILED DESIGN.
(AFTER ASIMOW).
KNOwLEDGE
1. ENGINEERING SCIENCES
2. ENGINEERING MATERIALS
3. ENGINEERING PROCESSES
4. ENGINEERING COSTS
5. SPECIAL COMPONENTS
6. DESIGN POLICY
7. PREVIOUS DESIGNS
8. COMPETITORS' PRODUCTS

FIG 2.2. THE DESIGN PROCESS.
Figure 2.3. Hierarchy of decisions in design.

Figure 2.4. The set of dominant design concepts. (From Asimow)
FIG 2.5. ORGANIZATION FOR PRODUCT PLANNING.

FIG 2.6. ANALYSIS OF NEW PRODUCT.
(AFTER ASIMOW)
Fig 2.7. An analogy of the mind.
(After von Fange)
DESIGN VARIABLES → MATHEMATICAL MODEL OF PRODUCT → OUTPUT - PERFORMANCE CHARACTERISTICS

**Fig 3.1. Block Diagram of Mathematical Model.**

![Diagram](image)

**Fig 3.2. Typical Operating Characteristic of Engineering Product.**
Fig 3.3. Probability of Sales.

Fig 3.4. Total Cost vs. Number of Models.
FIG 3.5. EXAMPLE OF A PLANNED RANGE OF CENTRIFUGAL PUMPS.
FIG 3.6. OPTIMIZATION OF SYSTEM WITH
ONE DESIGN VARIABLE, ONE OUTPUT VARIABLE.

FIG 3.7. OPTIMIZATION OF SYSTEM WITH
ONE DESIGN VARIABLE, TWO OUTPUT VARIABLES.
FIG 3.B. OPTIMIZATION OF SYSTEM WITH
TWO DESIGN VARIABLES, TWO OUTPUT VARIABLES.
CONTOURS OF $Y_1$
CONTOURS OF $Y_2$
$Y = 80 + 0.1x_1 + 0.2x_2 + 0.2x_1^2 + 0.1x_2^2 + x_1x_2$

Contours shown for $Y = 80$.

Dotted lines A, B, C, D are ridges for optimal responses.

Response along unit circle $R^2 = 1$.

Fig. 3.9. Example of ridge analysis for system with two variables (from Hoerl).
OPTIMA RESPONSE RIDGES.

\[ Y = 80 + 0.1x_1 + 0.2x_2 + 0.2x_1^2 + 0.1x_2^2 + x_1x_2 \]

\[ R^2 = x_1^2 + x_2^2. \]

CO-ORDINATES FOR MAXIMUM RIDGE.

FIG 3.10. EXAMPLE OF RIDGE ANALYSIS FOR
SYSTEM WITH TWO VARIABLES.
(FROM HOERL).
DRUM (WT = 16 LB)

FIG 3.11. DETAILS OF OVERHUNG ROTOR.

\[ R^2 = \sum x_i^2 = x_1^2 + x_2^2 + x_3^2 + x_4^2 \]

FIG 3.12. RESPONSE RIDGES FOR ROTOR CRITICAL SPEED.
(FROM LESTER)

FIG 3.13. RESPONSE RIDGES FOR ROTOR WEIGHT.
(FROM LESTER)
**Fig 3.14. Torsion Shaft.**

**Fig 3.15.** W versus d for shafts of different materials. Minimum value of W for each material is found from equation for ideal problem.

Materials are:
1. Steel AISI 4130
2. Ti Alloy
3. AL Alloy
4. Mg Alloy
5. Cast Phenolic
Fig 3.16. W versus l for shafts of different materials. Upper and lower limits of W have been found previously, see Fig 3.15.

Fig 3.17. C versus $x_{l_1}$. Determination of optimum design for case of normal specifications.
FIG. 3.18. \( C \) VERSUS \( x_L \), DETERMINATION OF OPTIMUM DESIGN FOR CASE OF REDUNDANT SPECIFICATIONS.

NUMBER OF LIMITED VARIABLES \((x_L) = n\). NUMBER OF SUBSIDIARY DESIGN EQUATIONS \((m) = n-1\).

IT IS ASSUMED THAT THREE MATERIALS ARE AVAILABLE, DENOTED (1), (2), AND (3).

THE CRITERION FUNCTION IS TO BE A MINIMUM.

THE LINES MARKED 1U, 1L etc. DEFINE THE UPPER AND LOWER LIMITS OF \( C \) WITHIN THE RANGE OF FEASIBLE DESIGNS FOR EACH MATERIAL. THE MINIMUM VALUE OF \( C \) WITHIN THIS RANGE DEFINES THE OPTIMUM DESIGN.
**Fig 3.19. Classical Mortality Curve.**

**Fig 3.20.**

*Fig 3.20. Failure Curves.*

**Fig 3.19.**

- **INFANT MORTALITY**
- **CONSTANT HAZARD**
- **WEAROUT**

**Fig 3.20.**

- **ACCEPTABLE NUMBER OF FAILURES**
- **PRODUCT LIFE**
- **TIME**

*(a) Typical Failure Curve for a Product.*

*(b) Effect of Preventive Maintenance.*
(1) ELEMENTS IN SERIES.

(2) ELEMENTS IN PARALLEL.

(3) SYSTEM STANDBY

(4) ELEMENT STANDBY

FIG 3.21. RELIABILITY BLOCK DIAGRAMS.
FIG 3.22. DECREASE OF RELIABILITY WITH TIME - WEAROUT FAILURES.

FIG 3.23. VARIATION OF RELIABILITY WITH TIME - CONSTANT HAZARD RATE FAILURES.
FIG 3.24. RELIABILITY BLOCK DIAGRAM OF MOTOR.

(a) HISTORIC APPROACH

(b) SYSTEMS APPROACH WITH MULTIPLE FEEDBACK.

FIG 3.25. IMPROVEMENT OF RELIABILITY.
FIG 3.26. METHODS OF IMPROVING RELIABILITY.
### Table: Relation Between Grades of Work and Machining Processes

<table>
<thead>
<tr>
<th>Machining Process</th>
<th>Normal TOL. ON 1&quot;</th>
<th>Fine TOL. ON 1/8&quot;</th>
<th>Coarse TOL. ON 1/4&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drill</td>
<td>.008</td>
<td>.005</td>
<td></td>
</tr>
<tr>
<td>Mill, Slot, Plane</td>
<td>.005</td>
<td>.002</td>
<td>.008</td>
</tr>
<tr>
<td>Turn, Bore</td>
<td>.002</td>
<td>.0012</td>
<td>.005</td>
</tr>
<tr>
<td>Ream</td>
<td>.0012</td>
<td>.0008</td>
<td></td>
</tr>
<tr>
<td>Comm’l Grind</td>
<td>.0012</td>
<td>.0008</td>
<td>.002</td>
</tr>
<tr>
<td>Fine Turn, Fine Bore</td>
<td>.0008</td>
<td>.0005</td>
<td></td>
</tr>
<tr>
<td>Hone</td>
<td>.0008</td>
<td>.0005</td>
<td></td>
</tr>
<tr>
<td>Broach</td>
<td>.0008</td>
<td>.0005</td>
<td></td>
</tr>
<tr>
<td>Fine Grind</td>
<td>.0005</td>
<td>.00025</td>
<td></td>
</tr>
<tr>
<td>Lap</td>
<td>.0005</td>
<td>.00025</td>
<td></td>
</tr>
</tbody>
</table>

**Relation Between Grades of Work and Machining Processes.**

**RUNNING AND SLIDING FITS**
- H7g6; H7f7; H8e8; H8d9; H9c9; H11c11.

**Locational and Assembly Fits**
- H6h6; H7h7; H8h8; H9h9; H11h11; H8a9; H8b9; H11h9.

**Transition Fits**
- H7j6; H7k6; H7m6.

**Interference Fits**
- H7p6; H7r6; H7u6.

**Recommended Fits for General Engineering. Classes of Fit are Designated According to B.S.1916: 1953 on “Hole Basis”**.

**Fig 4.1: Selection of Tolerances for Machined Parts.**
(After Gladman)
FIG 4.2. FREQUENCY DISTRIBUTION FOR A MACHINED DIMENSION.  
(FROM GLADMAN)
<table>
<thead>
<tr>
<th>DESIGN PLAN REVIEW</th>
<th>DRAFTING</th>
<th>CHECKING</th>
<th>P.D.R.C.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. PROVIDES SKETCHES &amp; COPIES OF DESIGN PLAN</td>
<td>3. PREPARES DESIGN LAYOUT USING RECOMMENDATIONS FROM DESIGN PLAN REVIEW</td>
<td></td>
<td>2. DESIGN PLAN REVIEW</td>
</tr>
<tr>
<td></td>
<td>4. PROVIDES COPIES OF DESIGN LAYOUT</td>
<td></td>
<td>5. DESIGN LAYOUT REVIEW</td>
</tr>
<tr>
<td></td>
<td>6. PREPARES DRAFTING INSTRUCTIONS WITH REVIEW RECOMMENDATIONS</td>
<td>7. PREPARES PRODUCTION DRAWINGS</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8. APPROVES DRAWINGS</td>
<td>9. CHECKS DRAWINGS</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10. INCORPORATES CHECKING CORRECTIONS REPRODUCES BLUEPRINTS</td>
<td></td>
<td>11. REVIEW OF PRODUCTION DRAWINGS</td>
</tr>
<tr>
<td></td>
<td>12. INCORPORATES RECOMMENDATIONS ON TRACINGS &amp; SENDS TO R.D.R.C. TO OBTAIN SIGNATURES</td>
<td>13. OBTAINS ALL APPROVAL SIGNATURES AND SENDS ALL TRACINGS TO RELEASE GROUP FOR FACTORY DISTRIBUTION</td>
<td></td>
</tr>
</tbody>
</table>

**Fig 4.3. The Product Design Review Committee.**
*(From Thomas)*
Fig 4.4. Organization of Design Cost Control in a Large Aircraft Company.
C.E. = Cost Engineer.
D.C.C.E. = Design Cost Control Engineer.
(from Van Hamersveld)
Author/s:
Lewis, William Powell

Title:
The design of engineering products

Date:
1963

Citation:

Publication Status:
Unpublished

Persistent Link:
http://hdl.handle.net/11343/36760

File Description:
The design of engineering products

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