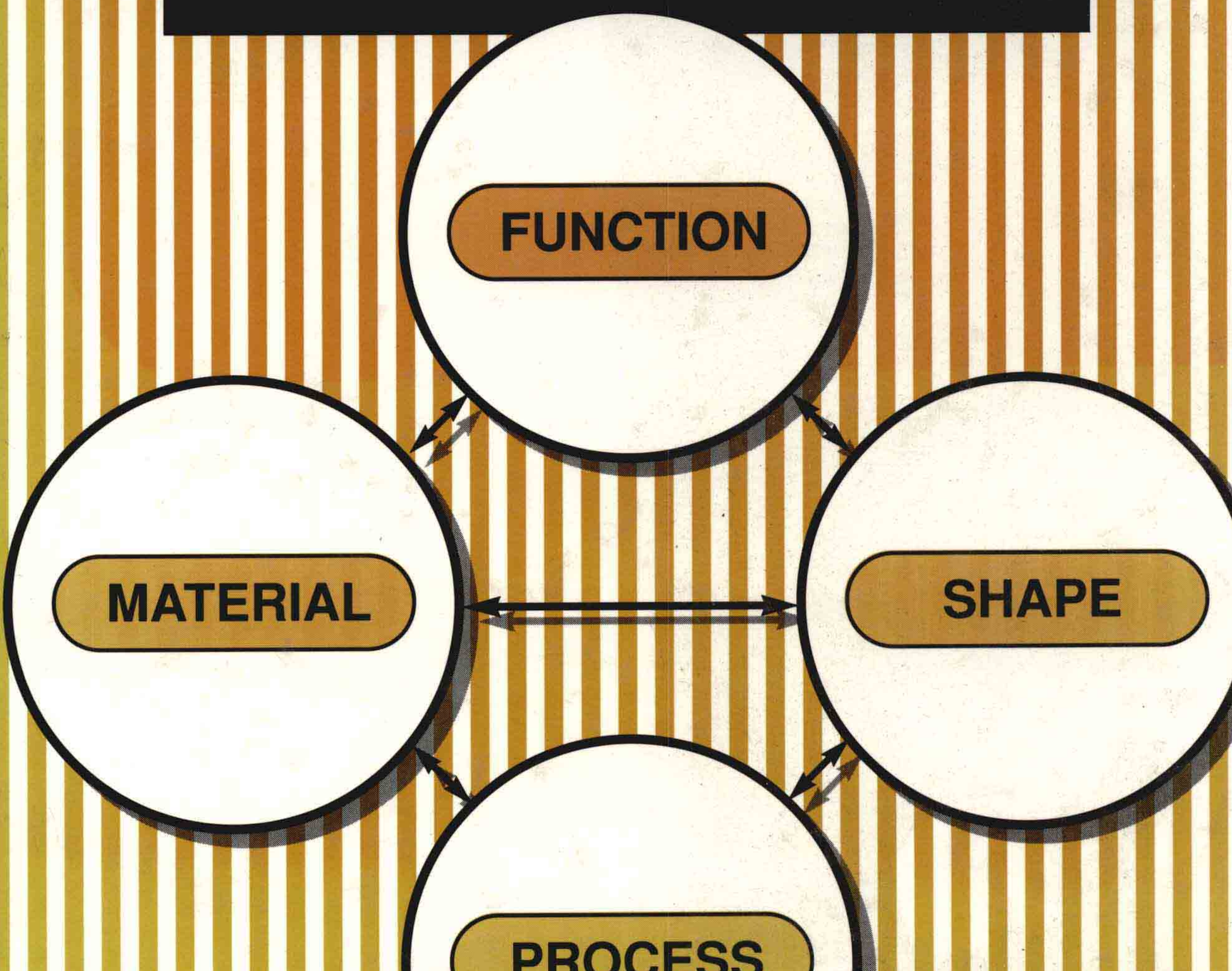
Materials Selection in Mechanical Design

M.F. Ashby



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Preface

"Materials are indifferent; but the use we make of them is not a matter of indifference" (EPICTETUS, AD 50 – 100, *Discourses*, Book 2, Chapter 5).

AN understanding of materials enabled advance in engineering design, even in Epictetus' time. Today, with more materials than ever before, the opportunities for innovation are immense. But advance is possible only if a procedure exists for making a rational choice. This book presents a procedure for material and process selection in mechanical design which allows the identification, from among the full range of materials and section shapes available to the engineer, of the subset most likely to perform well in a given application and for identifying the process by which the shape can be made. It is unique in the way the information it contains has been structured: the structure gives rapid access to data; it gives great freedom in exploring the potential of choice; and it allows a systematic scheme which isolates the optimum subset of material and process.

The approach of the book emphasises design with materials rather than materials "science", though the underlying science is used, whenever possible, to help with the structuring and in developing criteria for selection. The main part of the book requires little prior knowledge: a first-year engineering knowledge of materials and mechanics is enough; the parts dealing with shape are a little more advanced, but can be omitted on a first reading. The approach integrates materials selection with other aspects of design: the relationship with the stages of design and optimisation and with the mechanics of materials are developed throughout. At the teaching level, the book is intended as the text for third- and fourth-year engineering courses on Materials for Design: a 6 to 10 lecture unit can be based on Chapters 1 to 6; a full 20+ lecture course, with associated project work with the CMS software (described in Chapters 11 and 12), uses the entire book.

Beyond this, the book is intended as a reference text of lasting value. The method, the charts and tables of performance indices have application in real problems of materials and process selection; and the catalogue of "useful solutions" is particularly helpful in modelling — an essential ingredient of optimal design. The reader can use the book at increasing levels of sophistication as his or her experience grows — starting with the performance indices developed in the case studies of the text, and graduating to the modelling of new design problems, leading to new performance indices and new — perhaps novel — choices of material. This continuing education aspect is helped by a list of Further Reading at the end of each chapter, and by a set of problems covering all aspects of the text. Useful reference material is assembled in Appendices at the end of the book.

Like any other book, the contents of this one are protected by copyright. Generally, it is an infringement to copy and distribute material from a copyright source. But the best way to use the charts which are a feature of this book is to have a clean copy on which you can draw, try out alternative selection criteria, write comments, and present the conclusions to colleagues. Although the book itself is copyright, the reader is authorised to make copies of the charts, and to reproduce these, with proper reference to their source, as he or she wishes.

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CONTENTS

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CHAPTER 1

Introduction

1.1 Introduction and Synopsis

The word DESIGN means all things to all people. Every manufactured thing, from the most lyrical of ladies' hats to the greasiest of gearboxes, qualifies, in some sense or other, as a design. It can mean yet more. Nature to some is divine design; to others it is design by natural selection. The reader will agree that it is necessary to narrow the field, at least a little.

This book is about mechanical design, and the role of materials in it. Mechanical components have mass; they carry loads; they conduct heat; they are exposed to wear and to corrosive environments; they are made of one or more materials; they have shape; and they must be manufactured.

Materials have limited design since man first made clothes, built shelters and waged wars. They still do. But materials development is faster now than at any previous time in history; the challenges and opportunities they present are greater than ever before. The book is about exploiting materials in mechanical design.

1.2 Materials in Design

Design is the process of translating an idea or a market need into the detailed information from which a product can be made. Each of its stages requires decisions about the materials of which the product is to be made. Often the choice of material is dictated by the design. But sometimes it is the other way round: the new product, or the evolution of the existing one, was suggested or made possible by the new material. The number of materials available to the engineer is vast: something between 40,000 and 80,000 are at his or her (from here on "his" means both) disposal. And although standardisation strives to reduce the number, the continuing appearance of new materials with novel, exploitable, properties expands the choice further.

How, then, does the engineer choose, from this vast menu, the material best suited to his purpose? Can a procedure be formulated for making a rational choice? The question has to be answered at a number of levels, corresponding to the stage the design has reached. At the beginning the design is fluid and the option's are wide; all materials must be considered. As the design becomes more focused and takes shape, the selection criteria sharpen and the short list of materials which can satisfy them narrows. Then more accurate data are required (though for a lesser number of materials) and a different way of analysing the choice must be used. In the final stages of design, precise data are needed, but for still fewer materials — perhaps only for one. The procedure must recognise the initial richness of choice, yet also provide a method of narrowing it to a small subset on which design calculations can be based.

The choice of material cannot be made independently of the choice of process by which the material is to be formed, joined, finished, and otherwise treated. So processing is also an important aspect of design. Cost enters, both in the choice of material and in the way it is manipulated. And — it must be recognised — good mechanical design alone is not enough to sell a product. In almost everything from small home appliances through automobiles to aircraft, the form, texture, feel, colour, decoration of the product — the satisfaction it gives the person who buys or uses it — are important. This aesthetic aspect (known as "industrial design") is not treated in most courses on engineering; but it is one that, if neglected, can lose the manufacturer his market. Good designs work; excellent designs also give pleasure.

Design problems, almost always, are open-ended. They do not have a unique or "correct" solution, though some solutions will clearly be better than others. They differ from the analytical problems used in teaching mechanics, or structures, or thermodynamics, or even materials, which generally do have single, correct answers. So the first tool a designer needs is an open mind: the willingness to consider all possibilities. But a net cast widely draws in many fish. A procedure is necessary for selecting the best among them.

This book deals with the materials aspects of the design process. It develops a methodology which, properly applied, gives guidance through the confused sea of complex choices the designer faces. The idea of Materials Selection Charts is introduced; they make the initial survey for potential candidate materials particularly simple; and they allow a logical selection procedure to be implemented. The interaction between material and shape is discussed in detail, and databases and other sources of data appropriate to the later stages of design are reviewed. There is a treatment of the role of processing: Process Selection Charts are developed which direct the user to manufacturing processes capable of realising the design. The important role of aesthetics in engineering design is discussed. The forces driving change in the materials world are surveyed. The Appendices contain useful information: a compilation of results of mechanical and thermal analysis, helpful in modelling; and a catalog of the charts.

The methodology has further applications. It suggests a strategy for material development, particularly of composites and structured materials like sandwich panels. It points to a scheme for identifying the most promising applications for new materials. And it lends itself readily to computer implementation, offering the potential for interfaces with computer-aided design, function modelling, optimisation routines and so forth.

All this will be found in the following chapters, with case studies of applications. But first, a little history.

1.3 The Evolution of Engineering Materials

Throughout history, materials have limited design. The ages in which man has lived are named for the materials he used: stone, bronze, iron. And when he died, the materials he treasured were buried with him: Tutankamun with shards of coloured glass in his stone sarcophagus, Agamemnon with his bronze sword and mask of gold, each representing the high technology of his day.

If they had lived and died today, what would they have taken with them? Their titanium watch, their carbon fibre reinforced tennis racquet, their metal matrix composite mountain bike, their polyether ethylketone crash helmet. This is not the age of one material; it is the age of an immense range of materials. There has never been an era in which the evolution of materials was faster and the range of their properties more varied. The menu of materials available to the engineer has expanded so rapidly that designers who left college thirty years ago can be forgiven for not knowing that half of them exist. But not to know is, for the designer, to risk disaster. Innovative design often means the imaginative exploitation of the properties offered by new or improved materials. And for the man in the street, the schoolboy even, not to know is to miss one of the great developments of our age: the age of advanced materials.

This evolution and its increasing pace are illustrated in Fig. 1.1. The materials of prehistory (>10,000 BC, the Stone Age) were ceramics and glasses, natural polymers and composites. Weapons — always the peak of technology — were made of wood and flint; buildings and bridges of stone and wood. Naturally occurring gold and silver were available locally, but

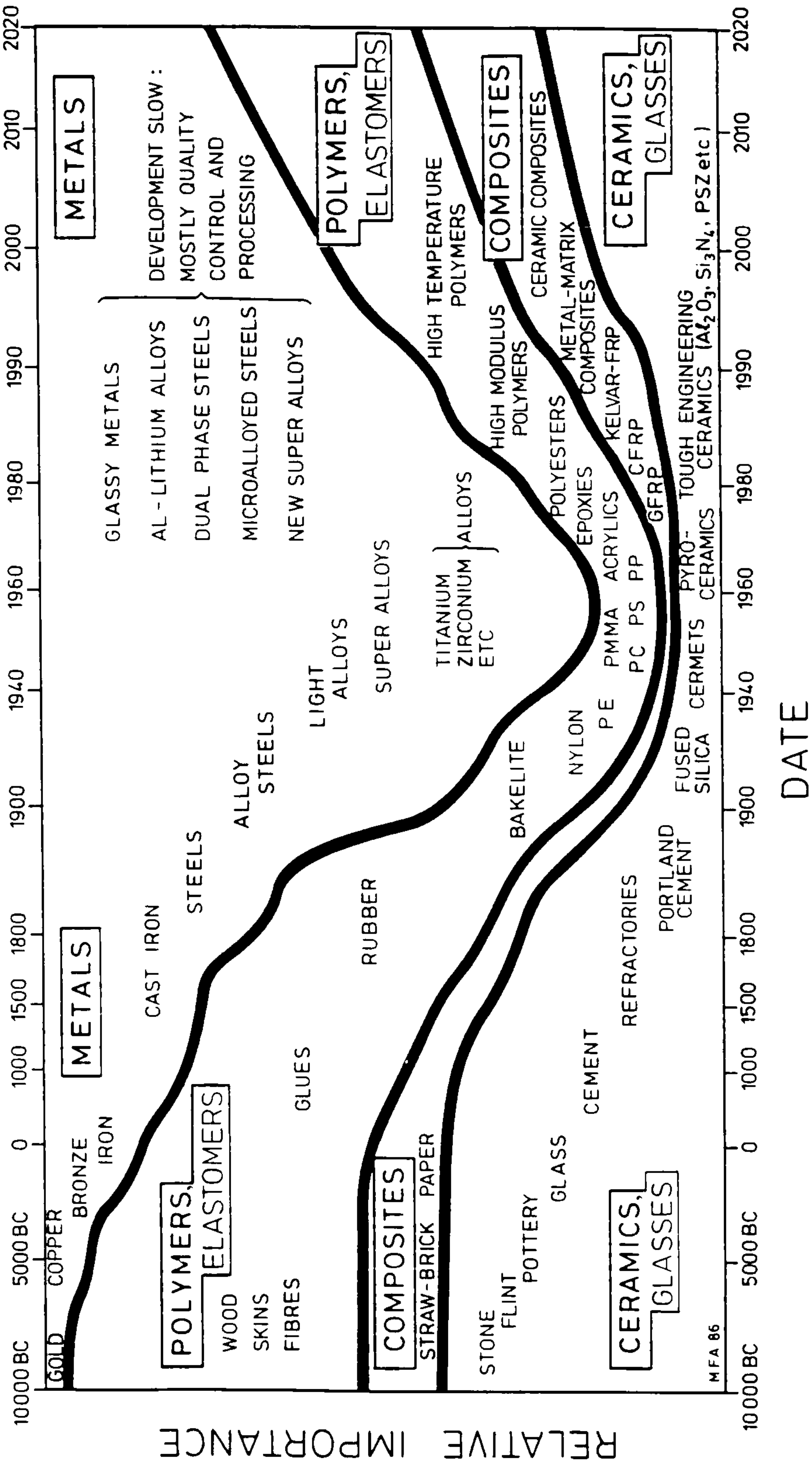

FIG. 1.1 The evolution of engineering materials.

played only a minor role in technology. The discovery of copper and bronze and then iron (the Bronze Age, 4000 BC to 1000 BC and the Iron Age, 1000 BC to AD 1620) stimulated enormous advances, replacing the older wooden and stone weapons and tools. Cast iron technology (1620 – 1850) established the dominance of metals in engineering; and the evolution of steels, light alloys and special alloys since then consolidated their position. By the 1960s, ''engineering materials'' meant ''metals''. Engineers were given courses in metallurgy; other materials were barely mentioned.

There had, of course, been developments in the other classes of material. Portland cement, refractories, fused silica among ceramics, and rubber, bakelite, and polyethylene among polymers, but their share of the total materials market was small. Since 1960 all that has changed. The rate of development of new metallic alloys is now slow; demand for steel and cast iron has actually fallen. The polymer and composite industries, on the other hand, are growing rapidly, and projections of the growth of production of the new high-performance ceramics suggests rapid expansion here also.

This rapid rate of change offers opportunities which the designer cannot afford to ignore.

1.4 Summary and Conclusions.

The number of engineering materials is large: estimates range from 40,000 to 80,000. The designer must select from this vast menu the material best suited to his task. This, without guidance, can be a difficult and tedious business, so that the temptation to choose the material that is ''traditional'' for the application is a strong one: glass for bottles; steel cans. That choice may be safely conservative, but it rejects the opportunity for innovation. Engineering materials are evolving faster, and the choice is wider than ever before. Examples of products in which a novel choice of material has captured a market are as common as — well, plastic bottles. Or aluminium cans. It is important in the early stage of design, or of redesign, to examine the full materials menu, not rejecting options merely because they are unfamiliar. A procedure for doing this is developed in the following chapters.

1.5 Further Reading

Connoisseurs will tell you that in its 11th edition the *Encyclopedia Britannica* reached a peak of excellence which has not since been equalled. On matters of general and technical history it is the logical starting point. More specialised books on metals, ceramics, glass and plastics can be found in most libraries.

Encyclopedia Britannica, 11th edition (1910) The Encyclopedia Britannica Company, New York, USA.
Tylecoate, R. F. (1976) *A History of Metallurgy*. The Metals Society, London, UK.

CHAPTER 2

The Design Process

2.1 Introduction and Synopsis

It is *mechanical design* with which we are primarily concerned here; it deals with the physical principles, the proper functioning and the production of mechanical systems. This does not mean that we ignore *industrial design*, which speaks of pattern, form, colour, texture, and (above all) consumer appeal — that comes later. But the starting point is good mechanical design and the role of materials in it; and here it is helpful to distinguish three types: original design (a completely new idea), adaptive design (the evolution of a product), and variant design (the change of size or shape without change of function). Materials selection influences all three.

Our aim is to develop a methodology for materials selection in mechanical design, encompassing all three of these types. To do so we must first look briefly at the design process. Like most technical fields it is encrusted with its own special jargon: it cannot all be avoided. This chapter introduces some of the words and phrases — the vocabulary — of design, and the way in which materials selection enters the process.

2.2 Types of Design

Original design involves a new working principle (the ballpoint pen, the compact disc). In seeking original designs, the designer must range his thinking as widely as possible; he must consider all possible solutions; and he must choose, by some sensible procedure, between them. New materials can offer new, unique combinations of properties which enable original design. High-purity silicon enabled the transistor, high-purity glass the optical fibre, high coercive-force magnets the miniature earphone, high-temperature alloys, the gas turbine. Sometimes the new material suggests the new product, but often the new product demands the development of a new material: both turbine and nuclear technology have required the development of new metallic alloys, and they remain one of the driving forces behind current developments of ceramics and composites.

Adaptive or *developmental design* seeks an incremental advance in performance through a refinement of the working principle. Often this is made possible by developments in materials: polymers replacing metals in household appliances; carbon fibre replacing wood in sports goods. The appliance and the sports goods markets are both very large and very competitive.

Markets have frequently been won (and lost) by the way in which the manufacturer has exploited new materials in developing his product.

Variant design involves a change of scale or dimension or detailing without change of function or method of achieving it: the scaling up of boilers, or of pressure vessels, or of turbines, for instance. Change of scale may require change of material: model planes are made of balsa wood, full-scale planes of aluminium alloys; model boilers are made of copper, full-scale boilers of steel; and for good reasons.

2.3 Technical Systems

A *technical system* consists of *assemblies* and *components*, put together in a way that performs a *function*. It can be described and analysed in more than one way. One — based on the ideas of systems analysis — thinks of the flows of information, energy and materials into, and out of, the system: the system transforms inputs into outputs. An electric motor converts electrical into mechanical energy; a forging press takes and reshapes material; a burglar alarm collects, and converts, information (Fig. 2.1).

In this approach, the system is broken down into connected subsystems which perform unit functions: the resulting arrangement is called the *function structure* of the system. It is like describing a cat (the total system) as made up of a nervous system, a respiratory system, a vascular system, a digestive system, and so on. Their functions and the way they connect are the function structure. Alternative designs link the unit functions in alternative ways, combine functions, or split them. The function structure approach gives a systematic way of assessing design options. But it is not much help in choosing materials.

A second way of analysing the technical system is, for this purpose, better. It is the breakdown of the system into *assemblies* and *components* (Fig. 2.2). It is like describing the cat as made up of bone, muscle, skin, fur and so on, each made of cells of a particular sort. A bicycle is a technical system. A wheel is an assembly. It is made up of individual components: spokes, gears, the rim, and others. Each component is made of a material: different components of different materials.

Material selection is at the component level. Some components are standard, common to many designs: a wood screw, for instance; but even among standards there is a choice of material (the screw could be of brass, or mild steel, or stainless steel). Some are specific, unique to the design: then the designer must select the material, the shape, and the processing route. Function, material, shape and process interact: the interactions are the central theme of this book. More on this in a moment.

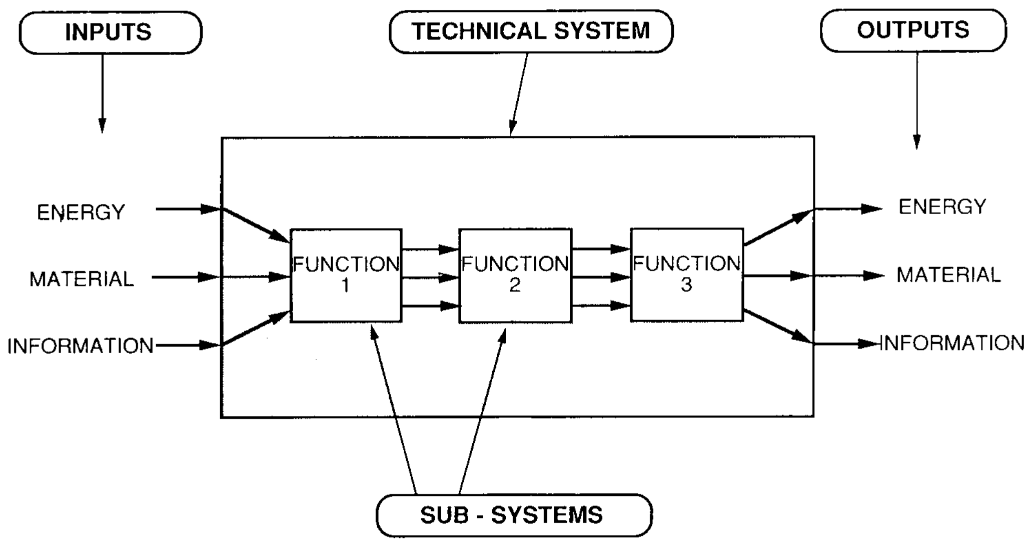

FIG. 2.1 The analysis of a technical system as a conversion of energy, materials and information (signals). This approach, when elaborated, helps structure thinking about alternative designs.

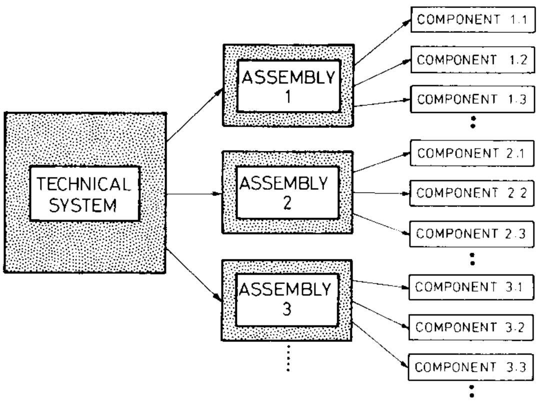

FIG. 2.2 The analysis of a technical system as a breakdown into assemblies and components. Materials selection is at the component level.

2.4 The Design Process

Design is an iterative process. The starting point is a market need or an idea; the end point is a product that fills the need or embodies the idea. Between lie a set of stages: the stages of *conceptual design, embodiment design* and *detailed design*, leading to a set of specifications — the production information — which define how the product should be made (Fig. 2.3). At the conceptual design stage all options are open: the designer considers the alternative working principles or schemes for the functions which make up the system, the ways in which subfunctions are separated or combined, and the implications of each scheme for performance and cost. Embodiment design takes a function structure and seeks to analyse its

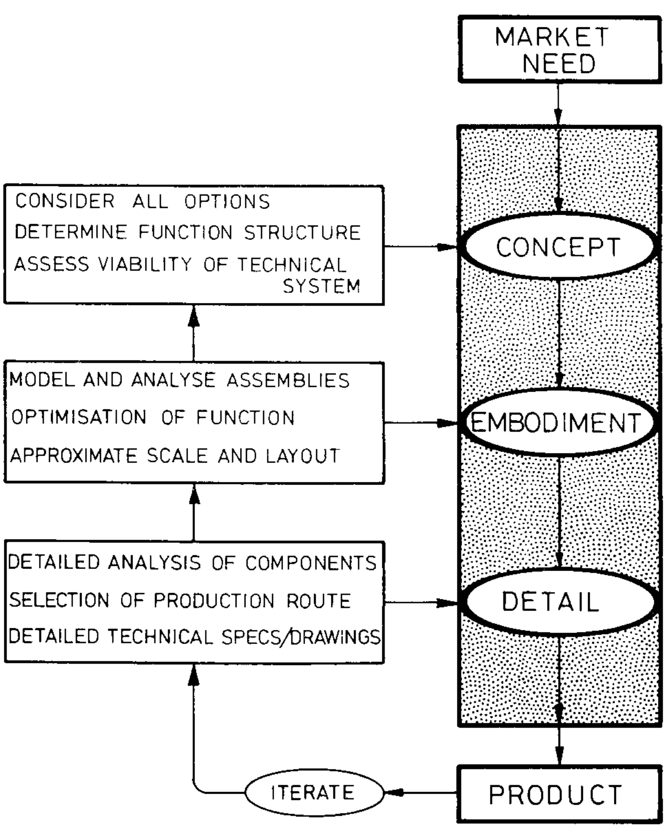

FIG. 2.3 The main design flow chart. The design proceeds from an identification of task through concept, embodiment and detailed specification

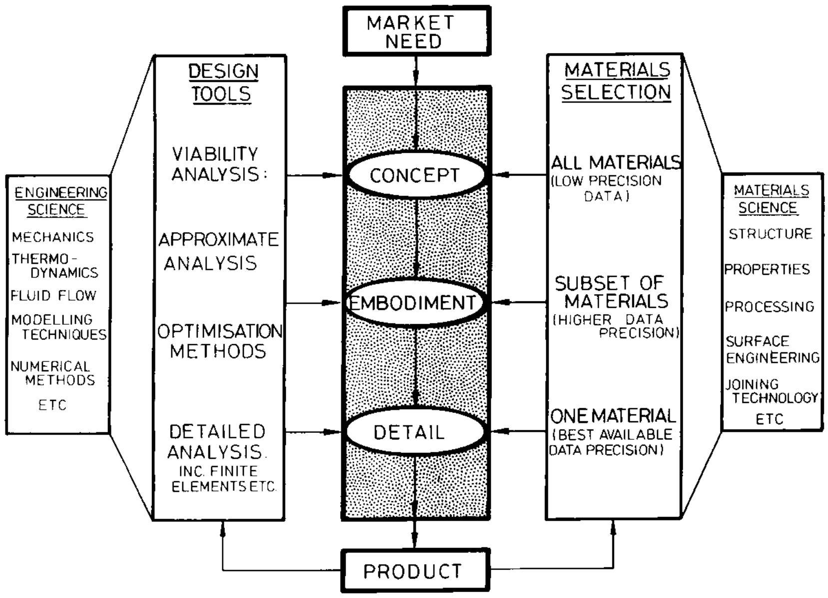

FIG. 2.4 The design flow chart, showing how design tools and materials selection enter the procedure. Information about materials is needed at each stage, but at very different levels of breadth and precision.

operation at an approximate level, sizing the components. and selecting materials which will perform properly in the ranges of stress, temperature and environment suggested by the analysis. The embodiment stage ends with a feasible layout which is passed to the detailed design stage. Here specifications for each component are drawn up; critical components may be subjected to precise mechanical or thermal analysis using finite element methods; optimisation methods are applied to components and groups of components to maximise performance; materials are chosen, the production route is analysed and the design is costed. The stage ends with detailed production specifications (Pahl and Beitz, 1984).[1]

2.5 Design Tools and Materials Data

To achieve all this, use is made of *design tools*. They are shown as inputs, attached to the main backbone of the design methodology (in Fig. 2.4). On the left are the tools of engineering science which allow the analysis, modelling and optimisation of the design: they are the principles and equations of mechanics, thermodynamics, techniques of modelling, and so forth. Increasingly, the routine aspects of design are eased by the use of computer-aided (CAD) design tools and by the use of databases which store information about standard components and configurations. There is a natural progression in the use of the tools as the design evolves: approximate analysis and modelling at the conceptual stage; more sophisticated modelling and optimisation at the embodiment stage; and detailed ("exact" — but nothing is ever that) analysis at the detailed design stage.

Materials selection enters at each stage of the design process (Fig. 2.4, right-hand column). The catalogue of materials is, as we have said, one of forbidding length. Increasing standardisation helps to reduce it, but any reduction is offset by the appearance of better alloys, stronger polymers, tougher ceramics, cleverer composites. The designer needs signposts to guide him through the maze of choices.

They are found in the constraints which each step in the design imposes on the choice of material, and in the results of *optimising* the performance and cost of the product. The conceptual design stage generates the first set of constraints — working temperature, environment, and such like. The subset of materials which satisfies these initial constraints

[1]References are listed under Further Reading in Section 2.9.

becomes the candidates for the next step. Further narrowing of the choice requires techniques of optimisation: the question is no longer: which materials will do the job? but: which will do it best? Here, iteration will be necessary: the material with the most desirable properties is seldom the one which is cheapest to shape, join and finish; optimisation of a different sort is necessary to evaluate the trade-offs between performance and overall cost. Detailed design can only proceed when the list of candidate materials for each component is reduced to one or a very few.

Data for material properties are needed at every stage in the design process. The nature of the data needed in the early stages differs greatly in its level of precision and breadth from that needed later on (Fig 2.4, right-hand side again). At the conceptual design stage, the designer requires approximate data for the widest possible range of materials. All options are open: a polymer may be the best choice for one concept, a metal for another, even though the function is the same. The problem, at this stage, is not precision; it is breadth and access: how can the vast range of data be presented to give the designer the greatest freedom in considering alternatives? A procedure which does this is developed in Chapters 5 and 6.

Embodiment design needs data for a subset of materials, but at a higher level of precision and detail. They are found in handbooks or in computer databases which contain the same information (Chapter 11). They list, plot and compare properties of a single class of materials — metals, for instance — and allow choice at a level of detail not possible from the broader compilations which include all materials.

The final stage of detailed design requires a still higher level of precision and detail, but for only one, or very few, materials. Such information is best found in the data sheets issued by the material producers themselves. A given material (polyethylene, for instance) has a range of properties, which derive from differences in the way different producers make it. At the detailed design stage, a supplier must be identified, and the properties of his product used in the design calculation; that from another supplier may be different. And sometimes even this is not good enough. If the component is a critical one (meaning that its failure could, in some sense or another, be disastrous) then it may be prudent to conduct in-house tests, measuring the critical property on a sample of the material that will be used to make the product itself.

The materials input into design does not end with the establishment of production. Products fail in service. Failures contain information. It is an imprudent manufacturer who does not collect and analyse data on failures. Almost always, this points up the misuse of a material, one which redesign or reselection can eliminate.

2.6 Function, Material, Shape and Process

The selection of a material cannot be separated from the choice of shape. We use the word "shape" to include the external shape and size (the macroshape), and — when necessary — the internal shape, as in a honeycomb or cellular structure (the microshape). To achieve the shape, the material is subjected to processes which, collectively, we shall call manufacture; they include primary forming processes (like casting and forging), material removal processes (machining, drilling), finishing processes (like polishing) and joining processes (like welding). Function, material, shape and process interact (Fig. 2.5). Function dictates the choice of material. The shape is chosen to perform the function using the material. Process is influenced by material properties: by formability, machinability, weldability, heat-treatability and so on. Process obviously interacts with shape — the process determines the shape, the size, the precision and, of course, the cost. The interactions are two-way: specification of shape restricts the choice of material; so, too, does specification of process. The more sophisticated the design, the tighter the specifications and the greater the interactions. It is like designing a wine: for cooking wine, almost any grape and fermentation process will do. For champagne, both grape and process are tightly constrained.

The interaction between function, material, shape and process lie at the heart of the material selection process. Later chapters focus on each in turn: — Chapters 5 and 6 describe the interaction of material and function; Chapters 7 and 8 are about the interaction of both of these with shape; Chapters 9 and 10 describe how process interacts with the other three.

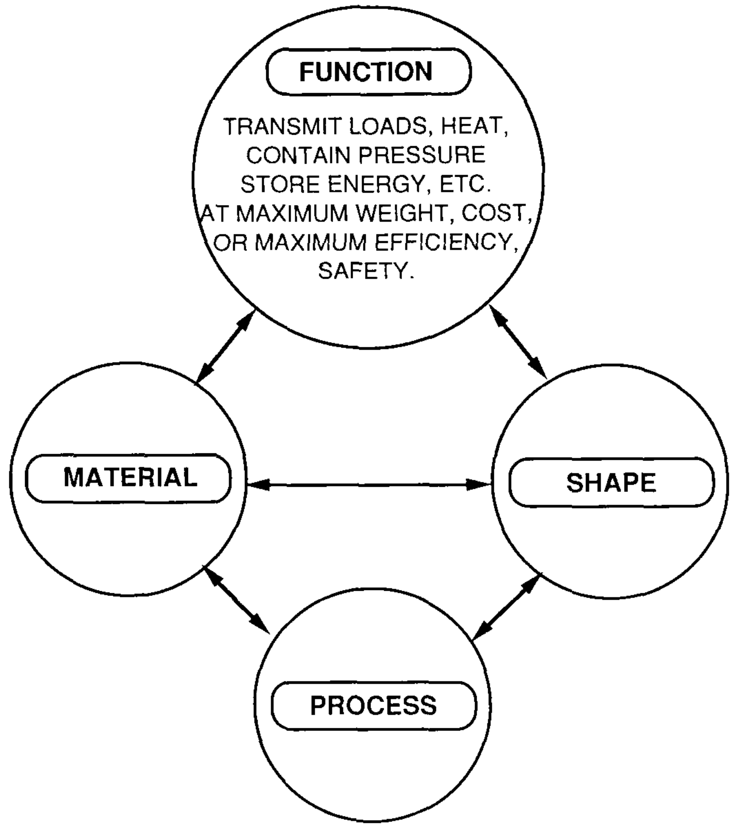

FIG. 2.5 The central problem of materials selection in mechanical design: the interaction between function, material, process and shape.

2.7 Case Study: The Design and Evolution of the Vacuum Cleaner

This chapter, so far, has been filled with abstractions. Here is something specific.

A *need* is perceived for a "device to remove dust from carpets in the home". Several *concepts* are possible: to suck the dust from the carpet with a vacuum; to blow it out with compressed air; to draw it out electrostatically; to trap it with an adhesive belt; to brush it out; all have been tried at one time or another. After a review the vacuum method is selected and a function structure is devised: it consists of a power source, a vacuum pump, a filter to catch the dust, and a tube to direct the action of the pump to the carpet. But in what order? The filter before or after the pump? Before: otherwise the dust goes through the pump. What power source? An electric motor, in a developed country; otherwise human — it is readily available. The concept is complete.

The *embodiment* stage involves more detailed calculations of low rates, pump design, form of the filter, diameter and length of the tube, the casing, the controls, and how they all fit together. When complete, a layout diagram with approximate dimensions, estimates of power, weight and performance exists.

There remains the *detailed design* of each of the components. As many as possible are standard; those which are not (the fan, for instance) may require a finite-element analysis for stress to ensure safety) or of air flow (to maximise efficiency or minimise noise). Production methods must be specified for each component and the relative costs of alternative methods must be analysed. An industrial designer advises on the shape, texture and colour of the external surfaces. The output is a complete set of engineering drawings with production specifications.

The vacuum cleaners of 1900 were human-powered (Fig. 2.6(a)). The housemaid, standing firmly on the flat base, pumped the handle of the cleaner, compressing bellows which, with leather flap valves to give a one-way flow, sucked air through a metal can containing the filter at a flow rate of about 1 litre per second. The butler manipulated the hose. The materials are