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, colour, texture, and (above all) consumer appeal — but that comes later. The starting point is good mechanical design, and the role of materials in it.

Our aim is to develop a methodology for selecting materials and processes which is *design-led;* that is, the selection uses, as inputs, the functional requirements of the design. To do so we must first look briefly at design itself. 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, the stages in its implementation, and the ways in which materials selection links with these.

2.2 The design process

Design is an iterative process. The starting point is a market need or a new idea; the end point is the full specifications of a product that fills the need or embodies the idea. It is essential to define the need precisely, that is, to formulate a *need statement,* often in the form: 'a device is required to perform task X'. Writers on design emphasize that the statement should be *solution-neutral* (that is, it should not imply how the task will be done), to avoid narrow thinking limited by pre-conceptions. Between the need statement and the product specification lie the set of stages shown in Figure 2.1: the stages of *conceptual design, embodiment design* and *detailed design.*

The product itself is called a *technical system.* A technical system consists of *assemblies, sub-assemblies* and *components***,** put together in a way that performs the required task, as in the breakdown of Figure 2.2. It is like describing a cat (the system) as made up of one head, one body, one tail, four legs, etc. (the assemblies), each composed of components — femurs, quadriceps, claws, fur. This decomposition is a useful way to analyse an existing design, but it is not of much help in the design process itself, that is, in the synthesis of new designs. Better, for this purpose, is one based on the ideas of systems analysis; it thinks of the inputs, flows and outputs of information, energy and materials, as in Figure 2.3. The design converts the inputs into the outputs. An electric motor converts electrical into mechanical energy; a forging press takes and reshapes material; a burglar alarm collects information and converts it to noise. In this approach, the system is broken down into connected subsystems which perform specific sub-functions, as in Figure 2.3; the resulting arrangement is called the *function structure* or *function decomposition* of the system. It is like describing a cat as an appropriate linkage of a respiratory system, a cardio-vascular system,

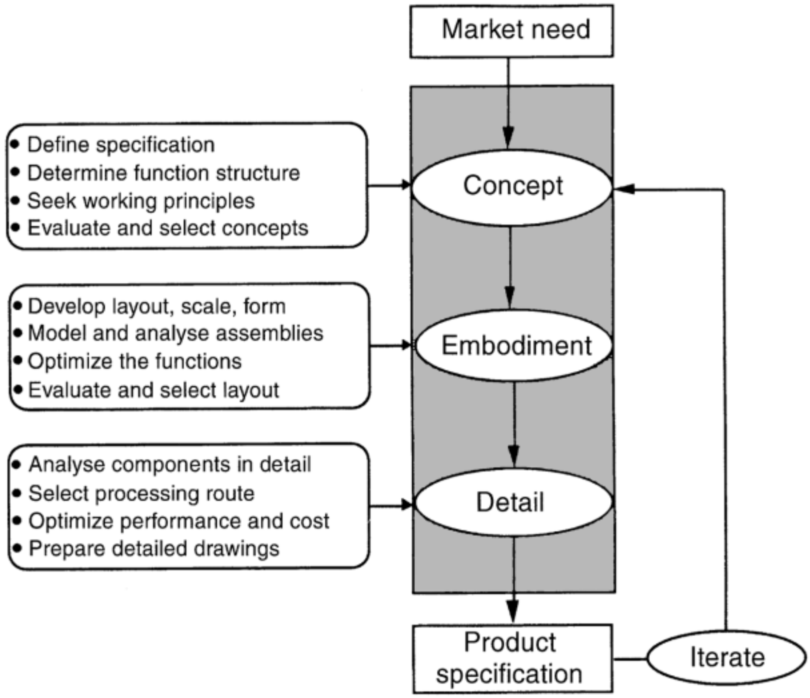

Fig. 2.1 The design flow chart. The design proceeds from an identification and clarification of task through concept, embodiment and detailed analysis to a product specification.

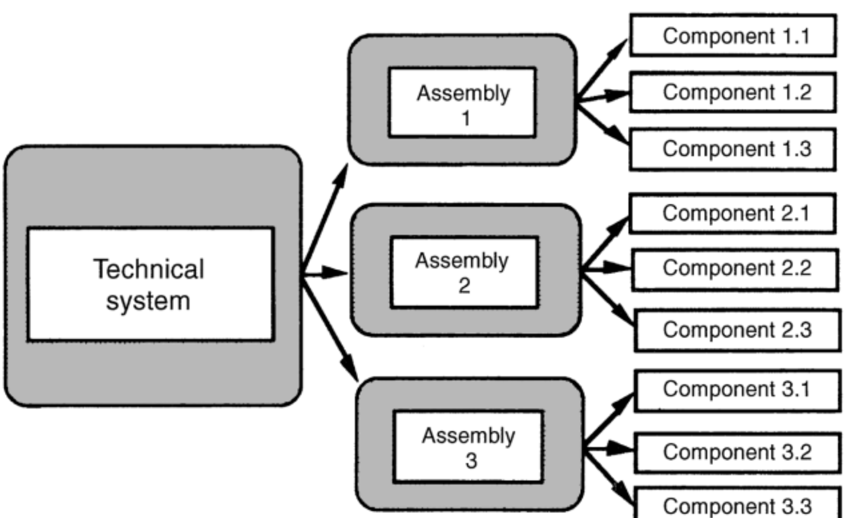

Fig. 2.2 The analysis of a technical system as a breakdown into assemblies and components. Material and process selection is at the component level.

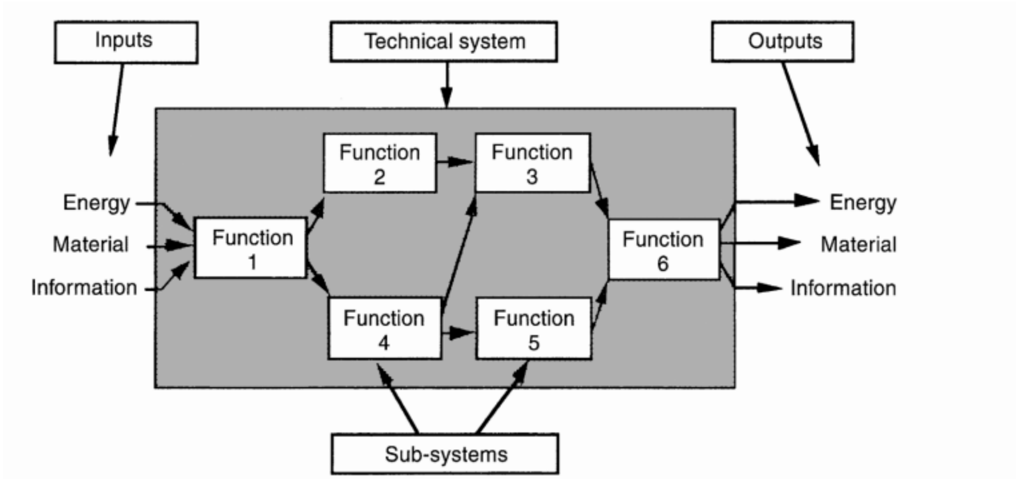

Fig. 2.3 The systems approach to the analysis of a technical system, seen as transformation of energy, materials and information (signals). This approach, when elaborated, helps structure thinking about alternative designs.

a nervous system, a digestive system and so on. Alternative designs link the unit functions in alternative ways, combine functions, or split them. The function-structure gives a systematic way of assessing design options.

The design proceeds by developing concepts to fill each of the sub-functions in the function structure, each based on a *working principle*. At this, the conceptual design stage (Figure 2.1 again), all options are open: the designer considers alternative concepts for the sub-functions and the ways in which these might be separated or combined. The next stage, embodiment, takes each promising concept and seeks to analyse its 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 or required by the specification, examining the implications for performance and cost. 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; optimization methods are applied to components and groups of components to maximize performance; a final choice of geometry and material is made, the production is analysed and the design is costed. The stage ends with detailed production specifications.

Described in the abstract, these ideas are not easy to grasp. An example will help — it comes in Section 2.6. First, a look at types of design.

2.3 Types of design

It is not always necessary to start, as it were, from scratch. *Original design* does: it involves a new idea or working principle (the ball-point pen, the compact disc). 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. Sometimes the new material suggests the new product; sometimes instead the new product demands the development of a new material: nuclear technology drove the development of a series of new zirconium-based alloys; space technology stimulated the development of lightweight composites; turbine technology today drives development of high-temperature alloys and ceramics.

Adaptive or *development design* takes an existing concept and seeks an incremental advance in performance through a refinement of the working principle. This, too, is often 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 market are both large and competitive. Markets here have frequently been won (and lost) by the way in which the manufacturer has exploited new materials.

Variant design involves a change of scale or dimension or detailing without change of function or the method of achieving it: the scaling up of boilers, or of pressure vessels, or of turbines, for instance. Change of scale or range of conditions may require change of material: small boats are made of fibreglass, large ones are made of steel; small boilers are made of copper, large ones of steel; subsonic planes are made of one alloy, supersonic of another; and for good reasons, detailed in later chapters.

2.4 Design tools and materials data

To implement the steps of Figure 2.1, use is made of *design tools*. They are shown as inputs, attached to the left of the main backbone of the design methodology in Figure 2.4. The tools enable the modelling and optimization of a design, easing the routine aspects of each phase. Function modellers suggest viable function structures. Geometric and 3-D solid modelling packages allow visualization and create files which can be downloaded to numerically controlled forming processes. Optimization, DFM, DFA* and cost-estimation software allow details to be refined. Finite element packages allow precise mechanical and thermal analysis even when the geometry is complex. 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 optimization at the embodiment stage; and precise ('exact' — but nothing is ever that) analysis at the detailed design stage.

Materials selection enters each stage of the design. The nature of the data needed in the early stages differs greatly in its level of precision and breadth from that needed later on (Figure 2.4, right-hand side). At the concept stage, the designer requires approximate property values, but 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? Selection systems exist which achieve this.

Embodiment design needs data for a subset of materials, but at a higher level of precision and detail. They are found in more specialized handbooks and software which deal with 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 a 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 calculations; that

* Design for Manufacture and Design for Assembly

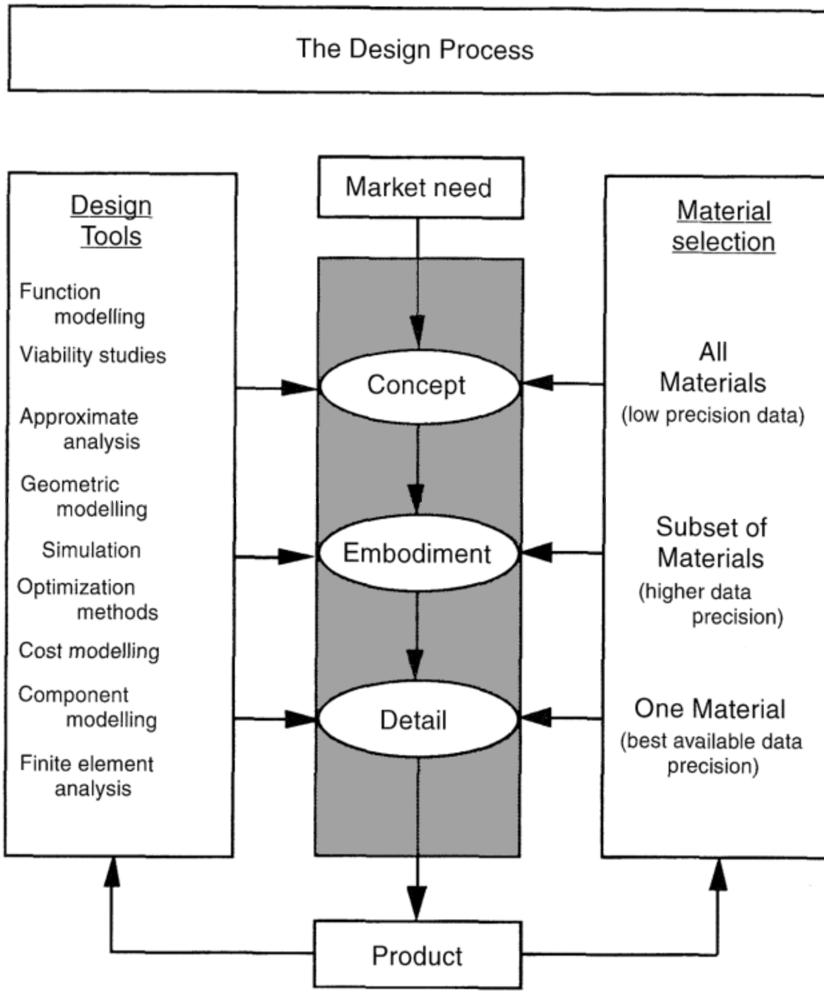

Fig. 2.4 The design flow chart, showing how design tools and materials selection enter the procedure. Information about materials is needed at each stage, but at very different levels of breadth and precision.

from another supplier may have slightly different properties. 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 to measure the critical properties, using a sample of the material that will be used to make the product itself.

It's all a bit like choosing a bicycle. You first decide which concept best suits your requirements (street bike, mountain bike, racing, folding, shopping...), limiting the choice to one subset. Then comes the next level of detail: how many gears you need, what shape of handlebars, which sort of brakes, further limiting the choice. At this point you consider the trade-off between weight and cost, identifying (usually with some compromise) a small subset which meet both your desires and your budget. Finally, if your bicycle is important to you, you seek further information in bike magazines, manufacturers' literature or the views of enthusiasts, and try the candidate bikes out yourself. Only then do you make a final selection.

The materials input into design does not end with the establishment of production. Products fail in service, and failures contain information. It is an imprudent manufacture who does not collect and analyse data on failures. Often this points to the misuse of a material, one which re-design or re-selection can eliminate.

2.5 Function, material, shape and process

The selection of a material and process cannot be separated from the choice of shape. We use the word 'shape' to include the external shape (the macro-shape), and — when necessary — the internal shape, as in a honeycomb or cellular structure (the micro-shape). The 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 (such as polishing) and joining processes (welding, for example). Function, material, shape and process interact (Figure 2.5). Function dictates the choice of both material and shape. Process is influenced by the material: by its 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 and process; but equally the specification of process limits the materials you can use and the shapes they can take. The more sophisticated the design, the tighter the specifications

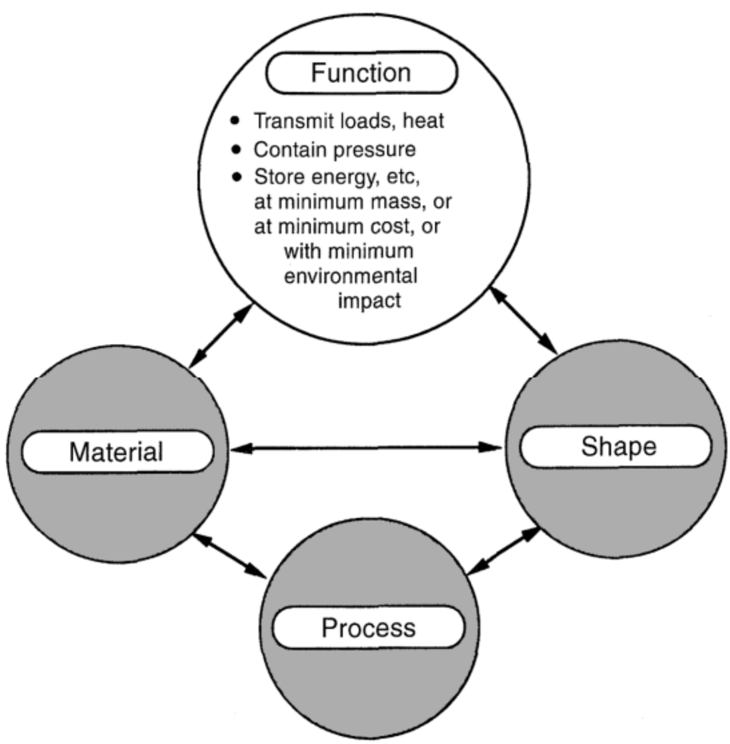

Fig. 2.5 The central problem of materials selection in mechanical design: the interaction between function, material, process and shape.

and the greater the interactions. It is like making wine: to make cooking wine, almost any grape and fermentation process will do; to make champagne, both grape and process must be tightly constrained.

The interaction between function, material, shape and process lies at the heart of the material selection process. But first: a case study to illustrate the design process.

2.6 Devices to open corked bottles

Wine, like cheese, is one of man's improvements on nature. And ever since man has cared about wine, he has cared about cork to keep it safely sealed in flasks and bottles. 'Corticum... demovebit amphorae...' — 'Uncork the amphora...' sang Horace* (27 BC) to celebrate the anniversary of his miraculous escape from death by a falling tree. But how did he do it?

A corked bottle creates a market need: it is the need to gain access to the wine inside. We might state it thus: 'a device is required to pull corks from wine bottles'. But hold on. The need must be expressed in solution-neutral form, and this is not. The aim is to gain access to the wine; our statement implies that this will be done by removing the cork, and that it will be removed by pulling. There could be other ways. So we will try again: 'a device is required to allow access to wine in a corked bottle' (Figure 2.6) and one might add, 'with convenience, at modest cost, and without contaminating the wine'.

Five concepts for doing this are shown in Figure 2.7. In sequence, they are to remove the cork by axial traction (= pulling); to remove it by shear tractions; to push it out from below; to pulverize it; and to by-pass it altogether — by knocking the neck off the bottle, perhaps.

Numerous devices exist to achieve the first three of these. The others are used too, though generally only in moments of desperation. We shall eliminate these on the grounds that they might

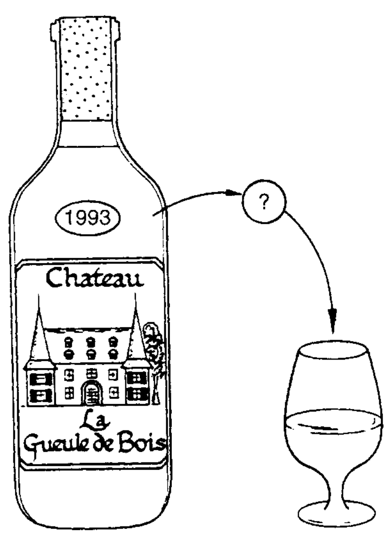

Fig. 2.6 The market need: a device is sought to allow access to wine contained in a corked bottle.

* Horace, Q. 27 BC, Odes, BOOK III, Ode 8, line 10.

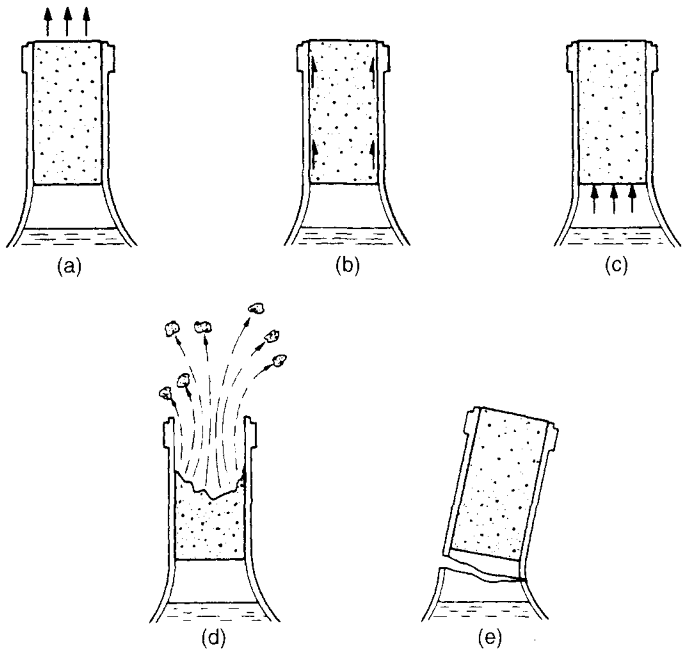

Fig. 2.7 Six possible concepts, illustrating physical principles, to fill the need expressed by Figure 2.6.

contaminate the wine, and examine the others more closely, exploring working principles. Figure 2.8 shows one for each of the first three concepts: in the first, a screw is threaded into the cork to which an axial pull is applied; in the second, slender elastic blades inserted down the sides of the cork apply shear tractions when pulled; and in the third the cork is pierced by a hollow needle through which a gas is pumped to push it out.

Figure 2.9 shows examples of cork removers using these working principles. All are described by the function structure sketched in the upper part of Figure 2.10: create a force, transmit a

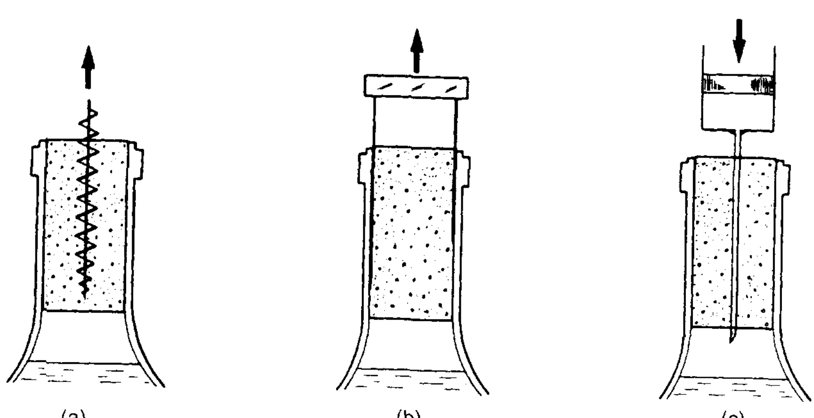

Fig. 2.8 Working principles for implementing the first three schemes of Figure 2.7.

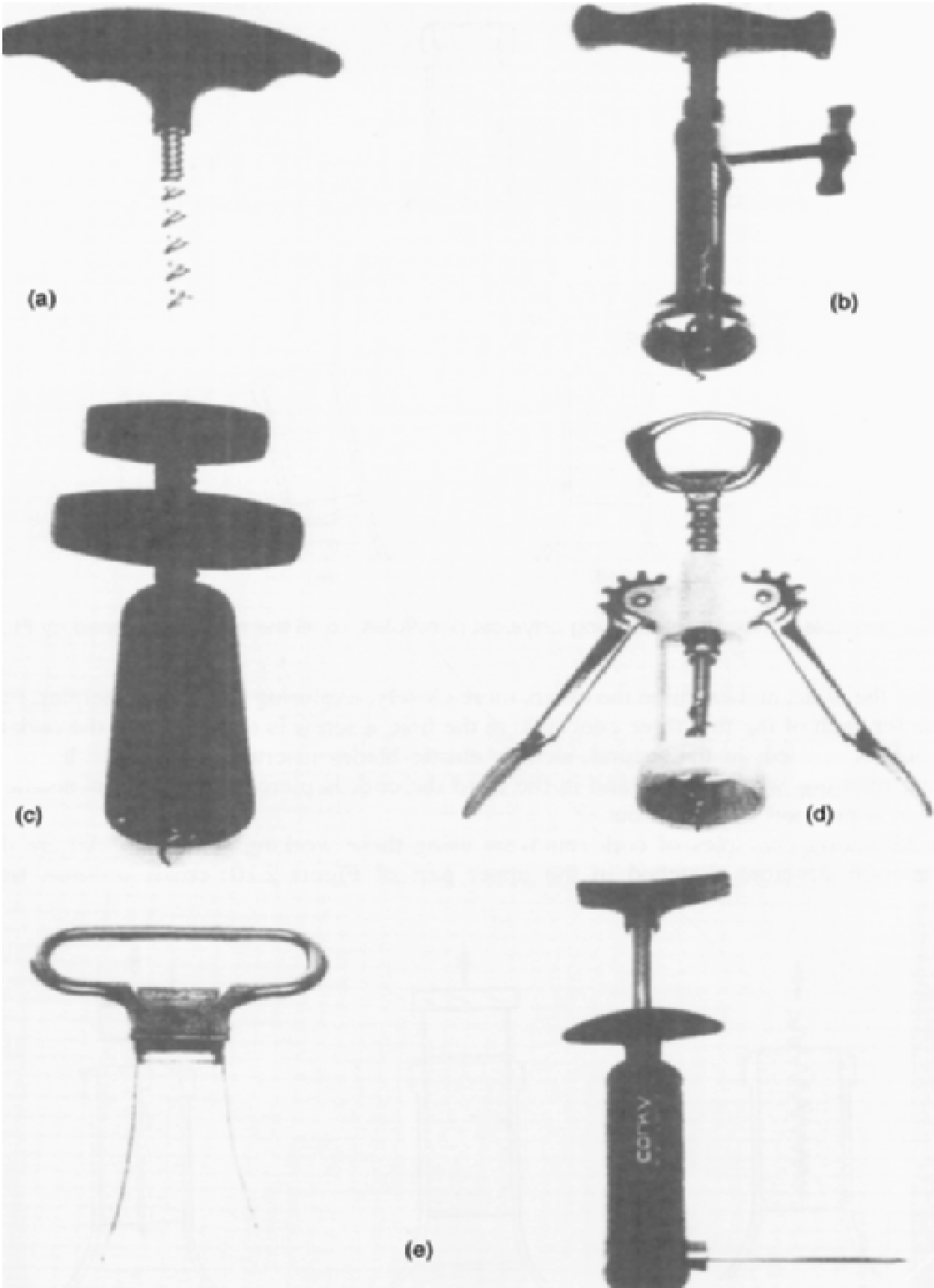

Fig. 2.9 Cork removers which employ the working principles of Figure 2.8: (a) direct pull; (b) gear lever, screw-assisted pull; (c) spring-assisted pull (a spring in the body is compressed as the screw is driven into the cork); (d) shear blade systems; (e) pressure-induced removal systems.

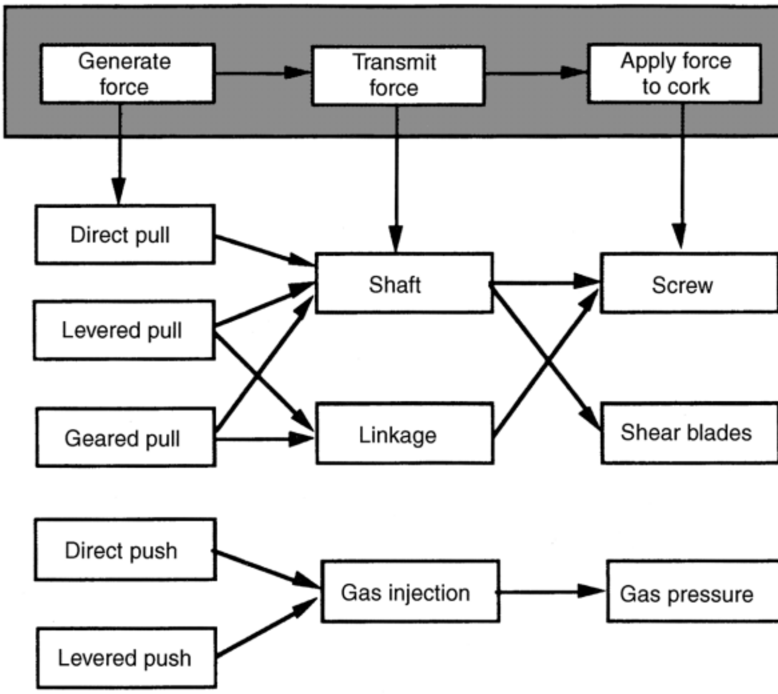

Fig. 2.10 The function structure and working principles of cork removers.

force, apply force to cork. They differ in the working principle by which these functions are achieved, as indicated in the lower part of Figure 2.10. The cork removers in the photos combine working principles in the ways shown by the linking lines. Others could be devised by making other links.

Figure 2.11 shows embodiment sketches for devices based on just one concept — that of axial traction. The first is a direct pull; the other three use some sort of mechanical advantage — levered pull, geared pull and spring-assisted pull; the photos show examples of all of these.

The embodiments of Figure 2.8 identify the *functional requirements* of each component of the device, which might be expressed in statements like:

- a light lever (that is, a beam) to carry a prescribed bending moment;
- a cheap screw to transmit a prescribed load to the cork;
- a slender elastic blade which will not buckle when driven between the cork and bottleneck;
- a thin, hollow needle strong enough to penetrate a cork;

and so on. The functional requirements of each component are the inputs to the materials selection process. They lead directly to the *property limits* and *material indices* of Chapter 5: they are the first step in optimizing the choice of material to fill a given requirement. The procedure developed there takes requirements such as 'light strong beam' or 'slender elastic blade' and uses them to identify a subset of materials which will perform this function particularly well. That is what is meant by *design-led material selection.*

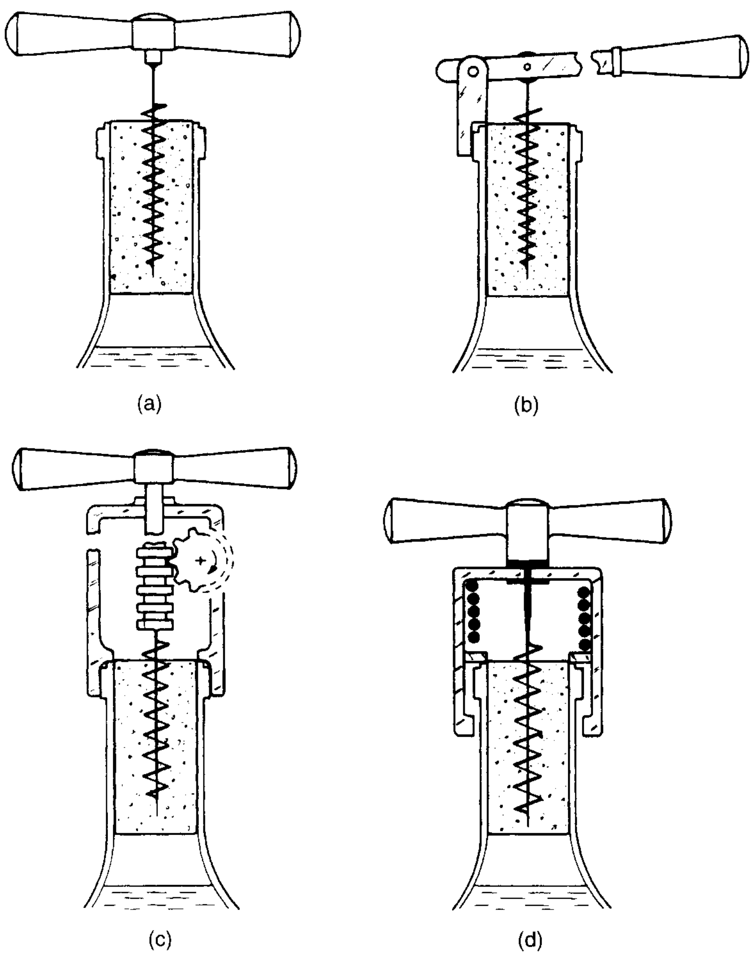

Fig. 2.11 Embodiment sketches for four concepts: direct pull, levered pull, geared pull and spring-assisted pull. Each system is made up of components which perform a sub-function. The requirements of these sub-functions are the inputs to the materials selection method.

2.7 Summary and conclusions

Design is an iterative process. The starting point is a *market need* captured in a *need statement.* A *concept* for a product which meets that need is devised. If initial estimates and exploration of alternatives suggest that the concept is viable, the design proceeds to the *embodiment* stage: working principles are selected, size and layout are decided, and initial estimates of performance and cost are made. If the outcome is successful, the designer proceeds to the *detailed design* stage: optimization of performance, full analysis (using computer methods if necessary) of critical components, preparation of detailed production drawings, specification of tolerance, precision, joining methods, finishing and so forth.

Materials selection enters at each stage, but at different levels of breadth and precision. At the conceptual stage all materials and processes are potential candidates, requiring a procedure which allows rapid access to data for a wide range of each, although without the need for great precision. The preliminary selection passes to the embodiment stage, the calculations and optimizations of which require information at a higher level of precision and detail. They eliminate all but a small shortlist of options which contains the candidate material and processes for the final, detailed stage of the design. For these few, data of the highest quality are necessary.

Data exist at all these levels. Each level requires its own data-management scheme, described in the following chapters. The management is the skill: it must be design-led, yet must recognize the richness of choice and embrace the complex interaction between the material, its shape, the process by which it is given that shape, and the function it is required to perform.

Given this complexity, why not opt for the safe bet: stick to what you (or others) used before? Many have chosen that option. Few are still in business.

2.8 Further reading

A chasm exists between books on Design Methodology and those on Materials Selection: each largely ignores the other. The book by French is remarkable for its insights, but the word 'Material' does not appear in its index. Pahl and Beitz has near-biblical standing in the design camp, but is heavy going. Ullman is a reduced version of Pahl and Beitz, and easier to digest. The book by Charles, Crane and Furness and that by Farag present the materials case well, but are less good on design. Lewis illustrates material selection through case studies, but does not develop a systematic procedure. The best compromise, perhaps, is Dieter.

General texts on design methodology

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McKearin, H. (1973) On 'stopping', bottling and binning, *International Bottler and Packer*, April, pp. 47–54.
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