CHAPTER 2

The Design Process

Cork removers. (Image courtesy of A-Best Fixture Co., Akron, Ohio.)

CONTENTS

Materials Selection in Mechanical Design. DOI: 10.1016/B978-1-85617-663-7.00002-3

2.1 INTRODUCTION AND SYNOPSIS

We are primarily concerned here with *mechanical design*: the physical principles, the proper functioning, and the production of mechanical systems. This does not mean that we ignore *industrial design*—pattern, color, texture, and (above all) consumer appeal—but that comes later. The optimum starting point in product development is good mechanical design, and the ways in which the selection of materials and processes contribute to it.

Our aim is to develop a methodology for selecting materials and processes that is *design-led*; that is, it uses, as inputs, the functional requirements of the design. To do so we must first look briefly at the design process itself. Like most technical fields, mechanical design is encrusted with its own special jargon, some of it bordering on the incomprehensible. We need very little, but 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

The starting point of a design is a *market need* or a *new idea*; the end point is the full *specification* of a product that fills the need or embodies the idea. A need must be identified before it can be met. It is essential to define the need precisely—that is, to formulate a *need statement*, often in this form: “A device is required to perform task X,” expressed as a set of *design requirements*. Writers on design emphasize that the need statement should be solution-neutral (that is, it should not imply how the task will be performed) to avoid narrow thinking constrained by preconceptions. Between the need statement and the product specification lie the stages shown in Figure 2.1: *concept, embodiment,* and *detailed design*, explained in a moment.

The product itself is called a *technical system*. A technical system consists of *subassemblies* 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, and so on (the subassemblies), each composed of components: femurs, quadriceps, claws, fur. This decomposition is a useful way to analyze an existing design, but it is not of much help in the design process itself, that is, in devising new designs. Better, for this purpose, is one based on the ideas of systems analysis, which considers the inputs, flows, and outputs of information, energy, and materials, as in Figure 2.3.

This design converts the inputs into the outputs. An electric motor, for example, converts electrical into mechanical energy; a forging press takes

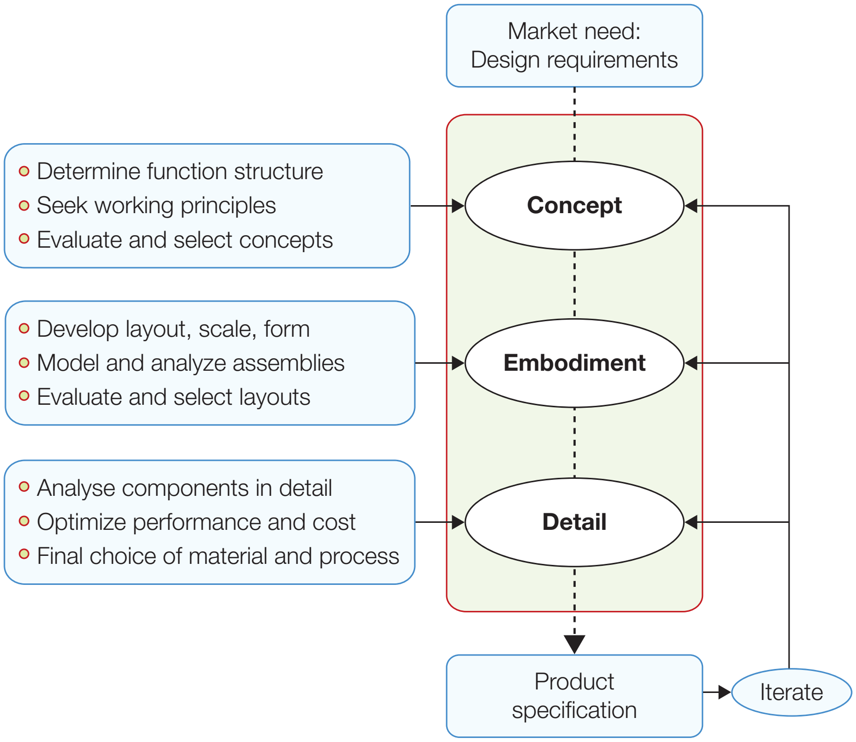

FIGURE 2.1
The design flow chart. The design proceeds from the identification of a *market need*, clarified as a set of *design requirements*, through *concept*, *embodiment*, and *detailed analysis* to a *product specification.*

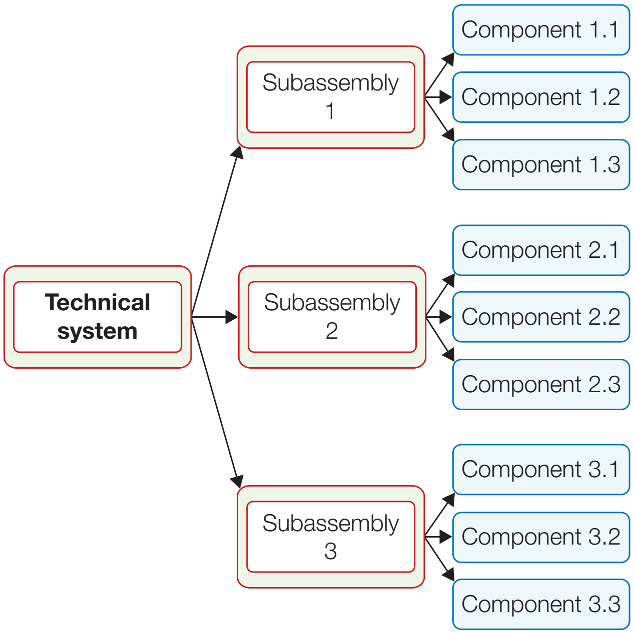

FIGURE 2.2
The analysis of a technical system as a breakdown into assemblies and components. Material and process selection is at the component level.

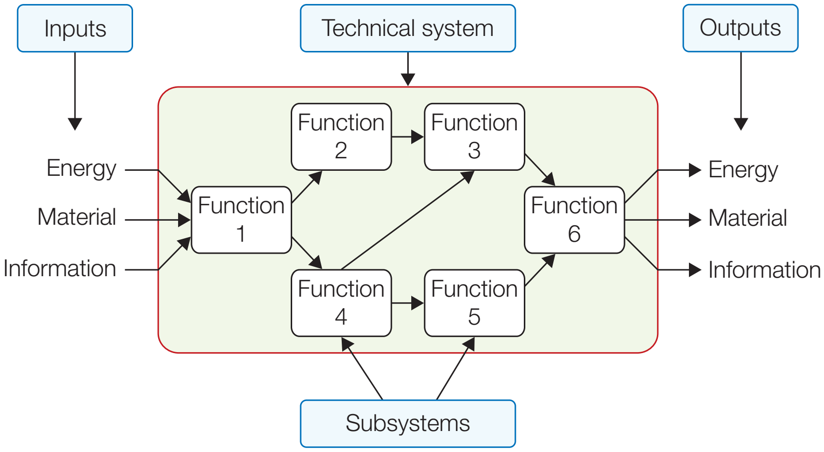

FIGURE 2.3

The function structure is a 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.

and reshapes material; a burglar alarm collects information and converts it to noise. In this approach, the system is broken down into connected subsystems, each of which performs a specific function, as shown 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, 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 perform the functions in the function structure, each based on a *working principle*. At this, the conceptual design stage, all options are open: The designer considers alternative concepts and the ways in which these might be separated or combined. The next stage, embodiment, takes the promising concepts and seeks to analyze their operation at an approximate level. This involves sizing the components and selecting materials that will perform properly in the ranges of stress, temperature, and environment suggested by the design requirements, examining the implications for performance and cost. The embodiment stage ends with a feasible layout, which is then 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 and the methods of production are analyzed and costed. The stage ends with a detailed production specification.

All that sounds well and good. If only it were so simple. The linear process suggested by Figure 2.1 obscures the strong coupling between the three stages. The consequences of choices made at the concept or the embodiment stages may not become apparent until the detail is examined. Iteration, looping back to explore alternatives, is an essential part of the design process.

Think of each of the many possible choices that *could* be made as an array of blobs in design space, as shown in Figure 2.4. Here C1, C2… are possible concepts, and E1, E2… and D1, D2… are possible embodiments and detailed elaborations of them. The design process becomes one of creating paths and linking compatible blobs until a connection is made from the top (market need) to the bottom (product specification). Some trial paths have dead ends, some loop back. It is like finding a track across difficult terrain—it may be necessary to go back many times to go forward in the end. Once a path is found, it is always possible to make it look linear and logical (and many books do this), but the reality is more like Figure 2.4 than Figure 2.1.

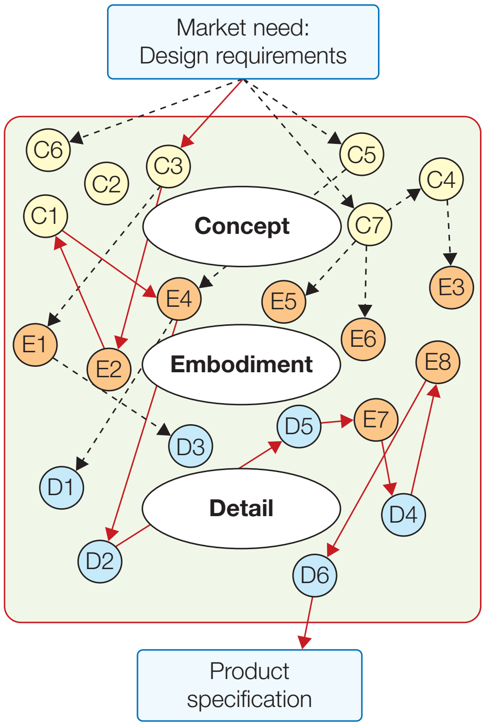

FIGURE 2.4

The convoluted path of design. Here the C-blobs represent concepts; the E-blobs, embodiments of the Cs; and the D-blobs, detailed realizations of the Es. The process is complete when a compatible path from "need" to "specification" can be identified. It is a devious path (the full red line) with back loops and dead ends (the broken lines). This creates the need for tools that allow fluid access to materials information at differing levels of breadth and detail.

Thus a key part of design, and of selecting materials for it, is *flexibility*, the ability to explore alternatives quickly, keeping the big picture as well as the details in mind. Our focus in later chapters is on the selection of materials and processes, where exactly the same need arises. This requires some kind of mapping of the "universes" of materials and processes to allow quick surveys of alternatives while still providing detail when it is needed. The selection charts of Chapter 4 and the methods of Chapter 5 help do this.

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 ballpoint pen, the compact disc). New materials can offer new, unique combinations of properties that enable original design. Thus high-purity silicon enabled the transistor; high-purity glass, the optical fiber; high coercive-force magnets, the miniature earphone; solid-state lasers the compact disc. 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 alloys and low-carbon stainless steels; space technology stimulated the development of light weight composites; gas turbine technology today drives development of high-temperature alloys and ceramic coatings. Original design sounds exciting, and it is. But most design is not like that.

Almost all design is *adaptive* or *developmental*. The starting point is an existing product or product range. The motive for redesigning it may be to enhance performance, to reduce cost, or to adapt it to changing market conditions. Adaptive design takes an existing concept and seeks an incremental advance in performance through a refinement of the working principle. It, too, is often made possible by developments in materials: polymers replacing metals in household appliances; carbon fiber replacing wood in sports equipment. The appliance and the sports equipment markets are fast-moving and competitive. These markets have frequently been won (and lost) by the way in which the manufacturer has adapted the product by exploiting new materials.

Finally, *variant design* involves a change of scale or dimension or detailing without a 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 circumstances of use may require change of material: Small boats are made of fiberglass, large ships are made of steel; small boilers are made of copper, large ones of steel; subsonic planes are made of one alloy, supersonic of another—all for good reasons, as 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 2.5. The tools enable the modeling and optimization of a design, easing the routine aspects of each phase. Function modelers suggest viable function structures. Configuration optimizers suggest or refine shapes. Geometric and 3D solid modeling packages allow visualization and create files that can be downloaded to numerically controlled prototyping and manufacturing systems. Optimization, DFM, DFA,[1] and cost estimation software allows manufacturing aspects to be refined. Finite element (FE) and computational fluid dynamics (CFD) packages allow precise mechanical and thermal analysis even when the geometry is complex, deformations are

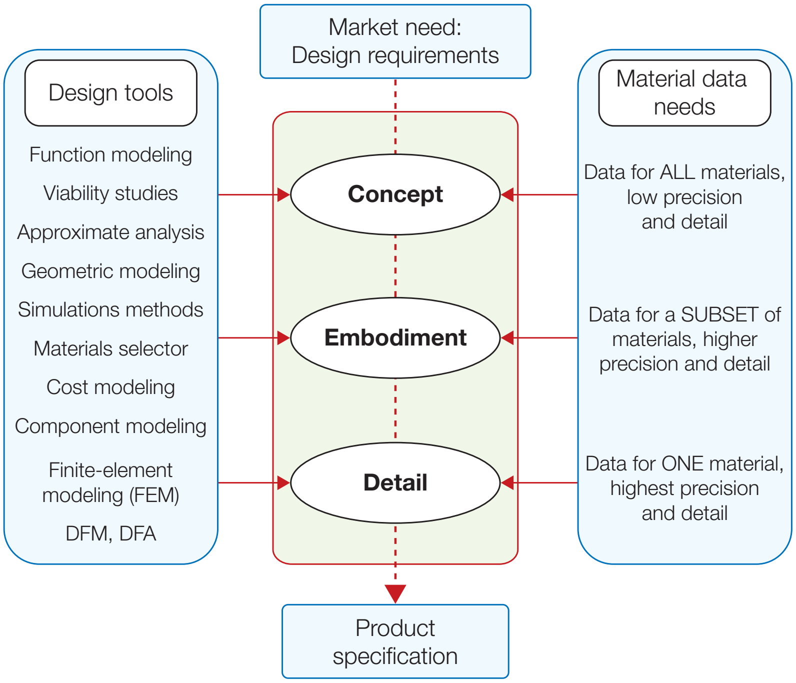

FIGURE 2.5
The design flow chart, showing how design tools and materials selection enter the procedure. Information about materials is needed at each stage, but at very different levels of breadth and precision. Iteration is part of the process.

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[1] Design for Manufacture and Design for Assembly.

large, and temperatures fluctuate. There is a natural progression in the use of the tools as the design evolves: approximate analysis and modeling at the conceptual stage; more sophisticated modeling and optimization at the embodiment stage; and precise ("exact"—but nothing is ever that) analysis at the detailed design stage.

Tools for material selection play a major part in 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 2.5, *right*). 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 and detail; it is breadth and speed of access: How can the vast range of data be presented to give the designer the greatest freedom in considering alternatives?

At the embodiment stage the landscape has narrowed. Here we need data for a subset of materials, but at a higher level of precision and detail. These are found in more specialized handbooks and software that deal with a single class or subclass of materials—*metals* or just *aluminum alloys*, for instance. The risk now is that of losing sight of the bigger spread of materials to which we must return if the details don't work out; it is easy to get trapped in a single line of thinking—a single set of "connections" in the sense of Figure 2.4—when other connections may offer a better solution.

The final stage, that 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 datasheets issued by the material producers themselves and in detailed databases for restricted material classes. A given material (polyethylene, for instance) has a range of properties that derive from differences in the ways different producers make it. At the detailed design stage, a supplier must be identified, and the properties of their product used in the design calculations; a product from another supplier may differ. 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 is 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.

The materials input does not end with the establishment of production. Products fail in service, and failures contain information. It is an imprudent manufacturer who does not collect and analyze data on failures. Often this points to the misuse of a material, one that redesign or reselection can eliminate.

So material choice depends on *function.* But that is not the only constraint.

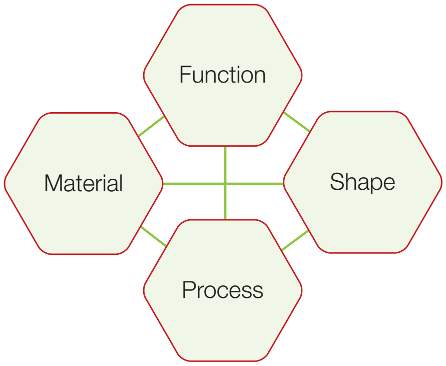

FIGURE 2.6
The central problem of materials selection in mechanical design: the interaction between function, material, process, and shape.

2.5 FUNCTION, MATERIAL, SHAPE, AND PROCESS

The selection of material is tied in with process and shape. To make a shape, the material is subjected to processes that, collectively, are called *manufacture*: these include primary forming processes (e.g., casting and forging), material removal processes (machining, drilling), joining processes (e.g., welding) and finishing processes (e.g., painting or electroplating). Function, material, shape, and process interact (Figure 2.6). Function, as already described, influences material choice. Material choice influences processes through the material's ability to be cast or molded or welded or heat-treated. Process determines shape; size; precision; and, of course, cost. These interactions are two-way: specification of shape restricts the choice of material and process; but equally the specification of process limits the material choice and the accessible shapes. The more sophisticated the design, the tighter the specifications and the greater the interactions.

The interaction between function, material, shape, and process lies at the heart of the material selection process. It is a theme we will return to throughout this book, visiting each of the hexagons of Figure 2.6 in turn. But first we look at a case study to illustrate the design process.

2.6 CASE STUDY: DEVICES TO OPEN CORKED BOTTLES

Wine, like cheese, is one of man's improvements on nature. And as long as humans have cared about wine, people have cared about corks to keep it safely sealed in flasks and bottles. "Corticum… demovebit amphorae…,"

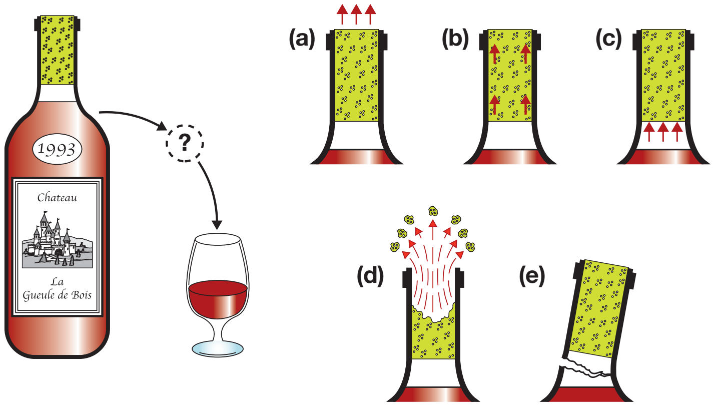

FIGURE 2.7

Left: the market need; a device is sought to allow access to wine contained in a corked bottle. *Right:* five possible concepts, illustrating physical principles, to fill the need.

("Uncork the amphora…)" sang Horace[2] 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: 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 the cork 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 2.7), and one might add, "with convenience, at modest cost, and without contaminating the wine."

Five concepts for doing this are shown on the right of Figure 2.7. In order, the devices act 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 bypass it altogether by knocking the neck off the bottle.[3]

Numerous devices exist that use the first three of these concepts. The others are used too, though generally only in moments of desperation. We shall eliminate these on the grounds that they might contaminate the wine, and examine the others more closely, exploring working principles. Figure 2.8 shows one example for each of the first three concepts: In the first, a screw

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[2] Horace, Q. 27 BC, *Odes*, Book III, Ode 8, line 10.

[3] A Victorian invention for opening old port, the cork of which may have become brittle with age and alcohol absorption, involved ring-shaped tongs. The tongs were heated red on an open fire, then clamped onto the cold neck of the bottle. The thermal shock removed the neck cleanly and neatly.

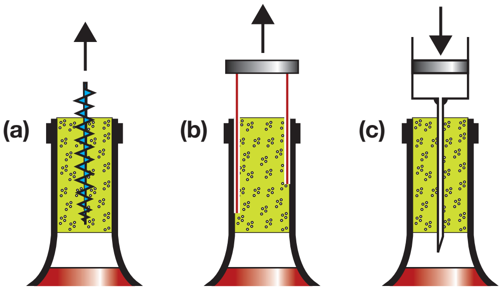

FIGURE 2.8

Working principles for implementing the first three concepts of Figure 2.7. Examples of all of these appear in the cover picture of this chapter.

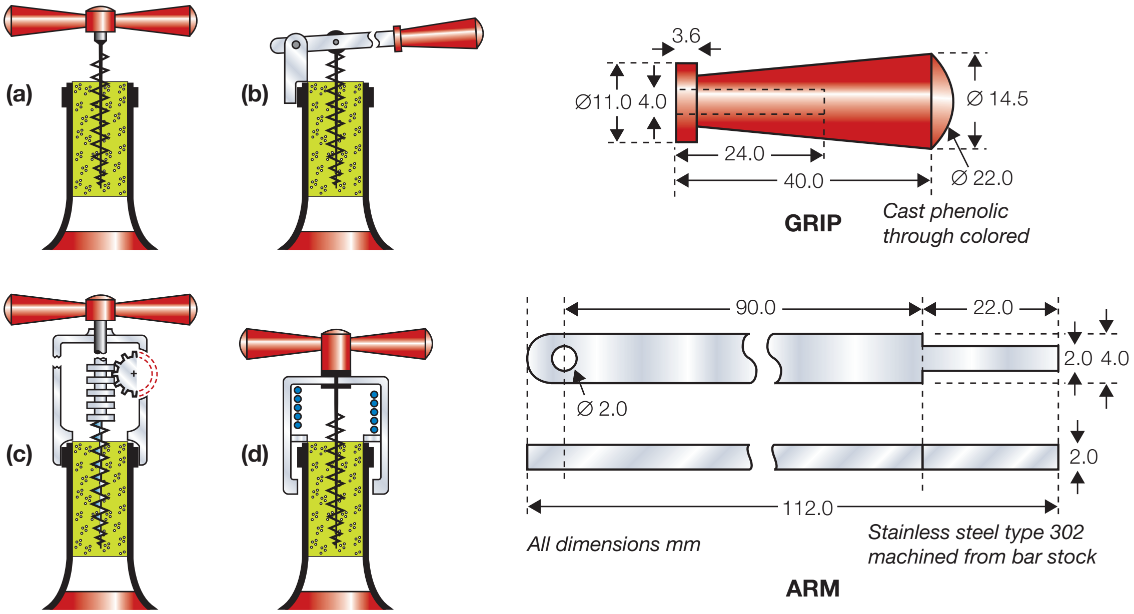

FIGURE 2.9

Left: embodiments: (a) direct pull; (b) lever-assisted pull; (c) gear-assisted pull; (d) spring-assisted pull (a spring in the body is compressed as the screw is driven into the cork). *Right:* detailed design of the lever of embodiment with material choice.

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 twisted and pulled; and in the third, the cork is pierced by a hollow needle through which a gas is pumped to push the cork out. Examples of all three appear in the cover picture of this chapter.

Figure 2.9 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 embodiments identify the *functional requirements*

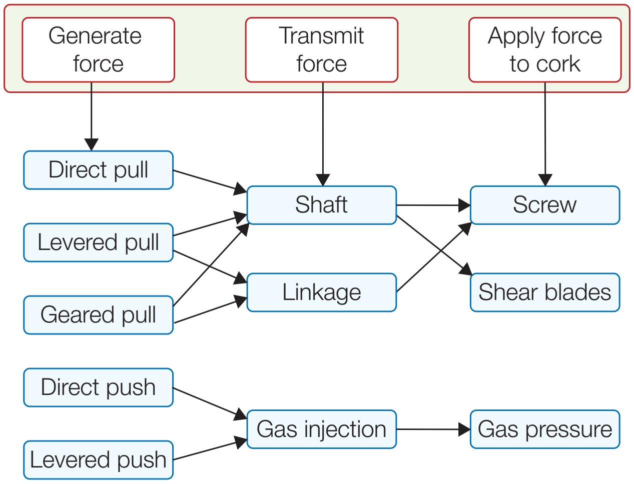

FIGURE 2.10

The function structure and working principles of cork removers.

of each component of the device, which might be expressed in statements such as

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

The functional requirements of each component are the inputs to the materials selection process. They lead directly to the *property limits* and *material indices*, as described in Chapter 5, in which we examine procedures with requirements such as "light, strong beam" or "slender, elastic, blade" and use them to identify a subset of materials that perform this function particularly well. The final choice of material and process forms part of the detailed stage of design (Figure 2.9), leading to full specifications to enable manufacture.

We conclude by returning to the idea of function structure. That for the cork remover is sketched in the upper part of Figure 2.10: Generate a force, transmit a force, apply the force to the cork. The alternative designs differ in the working principle by which these functions are achieved, as indicated in the lower part of the figure. Others could be devised by making other links.

2.7 SUMMARY AND CONCLUSIONS

Design is an iterative process. The starting point is a *market need* captured in a set of *design requirements. Concepts* for a product that meet the need are 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 of critical components, preparation of detailed production drawings (usually as CAD files), specifications of tolerance, precision, assembly, and finishing methods.

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 that 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 candidate materials and processes for the final, detailed stage of the design. For these few candidates, highest-quality data are required.

Data exist that meet the needs of all these levels. Each level requires its own data management scheme, described in the following chapters. The management system 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. And it must allow rapid iteration—back-looping when a particular path proves to be unprofitable. Tools now exist to help with all of this. We will meet one—the CES materials and process selection platform—later in this book.

But given this complexity, why not opt for the safe bet: Stick to what you 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 have near-biblical standing in the design camp, but their text is heavy going. Ullman and Cross take a more relaxed approach and are easier to digest. The books by Budinski and Budinski, by Charles, Crane, and Furness, and 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

Cross, N. (2000). *Engineering design methods* (3rd ed.). Wiley, ISBN 0-471-87250-4.

A durable text describing the design process, with emphasis on developing and evaluating alternative solutions.