Chapter one

Materials, processes and choice

1-1-Introduction-review:

Engineers make things. They make them out of materials. *The materials have to support loads, to insulate or conduct heat and electricity, to accept or reject magnetic flux, to transmit or reflect light, to survive in often-hostile surroundings, and to do all this without damage to the environment or costing too much*.

And there is the partner in all this. To make something out of a material you also need a process. Not just any process—the one you choose has to be compatible with the material you plan to use. *Sometimes it is the process that is the dominant partner and a material-mate must be found that is compatible with it.* Compatibility is not easily found, and material failure can be catastrophic, with issues of liability and compensation.

1-2-What is the meaning of design?

‘‘Design’’ is one of those words that means all things to all people. Every manufactured thing, from ladies’ hats to the greasiest of gearboxes, qualifies, in some sense or other, as a design. It can mean yet more.

Design *is the process of translating a new idea or a market need into the detailed information from which a product can be manufactured.*

Although engineers are not the only people who design things, it is true that the professional practice of engineering is largely concerned with design; it is often said that design is the essence of engineering. To design is to pull together something new or to arrange existing things in a new way to satisfy a recognized need of society. An elegant word for “pulling together” is synthesis. We shall adopt the following formal definition of design: “Design establishes and defines solutions to and pertinent structures for problems not solved before, or new solutions to problems which have previously been solved in a different way.”

The ability to design is both a science and an art. The science can be learned through techniques and methods to be covered in this text, but the art is best learned by doing design. It is for this reason that your design experience must involve some realistic project experience.

1-3- Types of design:

Engineering design can be undertaken for many different reasons, and it may take different forms:

● **Original design,** also called *innovative design*. it involves a new idea or working principle. *This form of design is at the top of the hierarchy*. It employs an *original, innovative concept to achieve a need*. Sometimes, but rarely, the need itself may be original. A *truly original design involves invention*. Successful original designs occur rarely, but when they do occur they usually disrupt existing markets because they have in them the seeds of new technology of far-reaching consequences. (the ball-point 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-based alloys and low-carbon stainless steels; space technology stimulated the development of light-weight composites; turbine technology today drives development of high-temperature alloys and ceramics.

- **Adaptive design** . This form of design occurs when the design team adapts a known solution to satisfy a different need to produce a novel application. For example, adapting the ink-jet printing concept to spray binder to hold particles in place in a rapid prototyping machine. Adaptive designs involve synthesis and are relatively common in design.

- **Redesign** . Much more frequently, engineering design is employed to improve an existing design. *The task may be to redesign a component in a product that is failing in service, or to redesign a component so as to reduce its cost of manufacture.*

Often redesign is *accomplished without any change in the working principle or concept of the original design*. For example, the shape may be changed to reduce a stress concentration, or a new material substituted to reduce weight or cost. *When redesign is achieved by changing some of the design parameters, it is often called* variant design.

- **Selection design.** Most designs employ *standard components* such as bearings, small motors, or pumps that are supplied by vendors specializing in their manufacture and sale. Therefore, in this case the design task consists of selecting the components with the needed performance, quality, and cost from the catalogs of potential vendors.

- **Industrial design**. This form of design deals with *improving the appeal of a product to the human senses, especially its visual appeal*. While this type of design *is more artistic than engineering*, it is a vital aspect of many kinds of design. Also *encompassed* by *industrial* design is *a consideration of how the human user can best interface with the product.*

- **Adaptive or developmental 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 fiber 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 adapted the product by exploiting 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 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; and for good reasons, detailed in later chapters.

1-4- Materials in design

As it said before, *Design is the process of translating a new idea or a market need into the detailed information from which a product can be manufactured.* Each of its stages requires decisions about the materials of which the product is to be made and the process for making it. *Normally, 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 over 120,000 are at designer`s disposal. And although standardization strives to reduce the number, the continuing appearance of new materials with novel, exploitable, properties expands the options further.

How, then, does the engineer choose, from this vast menu, the material best suited to his purpose? Must the designer rely on experience?

There is no question of the value of experience. But a strategy relying on experience-based learning is not in tune with the pace and re-dispersion of talent that is part of the age of information technology. We need a systematic procedure — one with steps that can be taught quickly, that is robust in the decisions it reaches, that allows of computer implementation, and with the ability to interface with the other established tools of engineering design.

At the beginning the design is fluid and the options 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 that can satisfy them narrows*. Then more ***accurate*** data are required (though for a lesser number of materials) and a different way of analyzing the choice must be used. In the *final stages of design, precise data are needed*, but for still fewer materials — perhaps only one. The procedure must recognize the initial richness of choice, and at the same time provide the precision and detail on which final 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. Cost enters both in the choice of material and in the way the material is processed. So, it too, does the influence material usage on the environment in which we live. And it must be *recognized that good engineering design alone is not enough to sell products*. In almost everything from home appliances through automobiles to aircraft, *the form, texture, feel, color, decoration of the product — the satisfaction it gives the person who owns or uses it — are important.* This aspect, known confusingly as ‘‘industrial design’’, 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, 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 excellent from the merely good.

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.

This evolution and its increasing pace are illustrated in Figure 1.1. The materials of pre-history (> 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 and, through their rarity, assumed great influence as currency, but their role in technology was small. The development of rudimentary thermo-chemistry allowed the extraction of, first, copper and bronze, then iron (the Bronze Age, 4000–1000 BC and the Iron Age, 1000 BC–1620 AD) stimulating enormous advances, in technology. Cast iron technology (1620s) established the dominance of metals in engineering; and since then the evolution of steels (1850 onward), light alloys (1940s) and special alloys, has consolidated their position. By the 1960s, ‘‘engineering materials’’ meant ‘‘metals’’.

There had, of course, been developments in the other classes of material.

Improved cements, refractories, glasses, and rubber, Bakelite, and poly-ethylene among polymers, but their share of the total materials market was small. Since 1960 all that has changed.

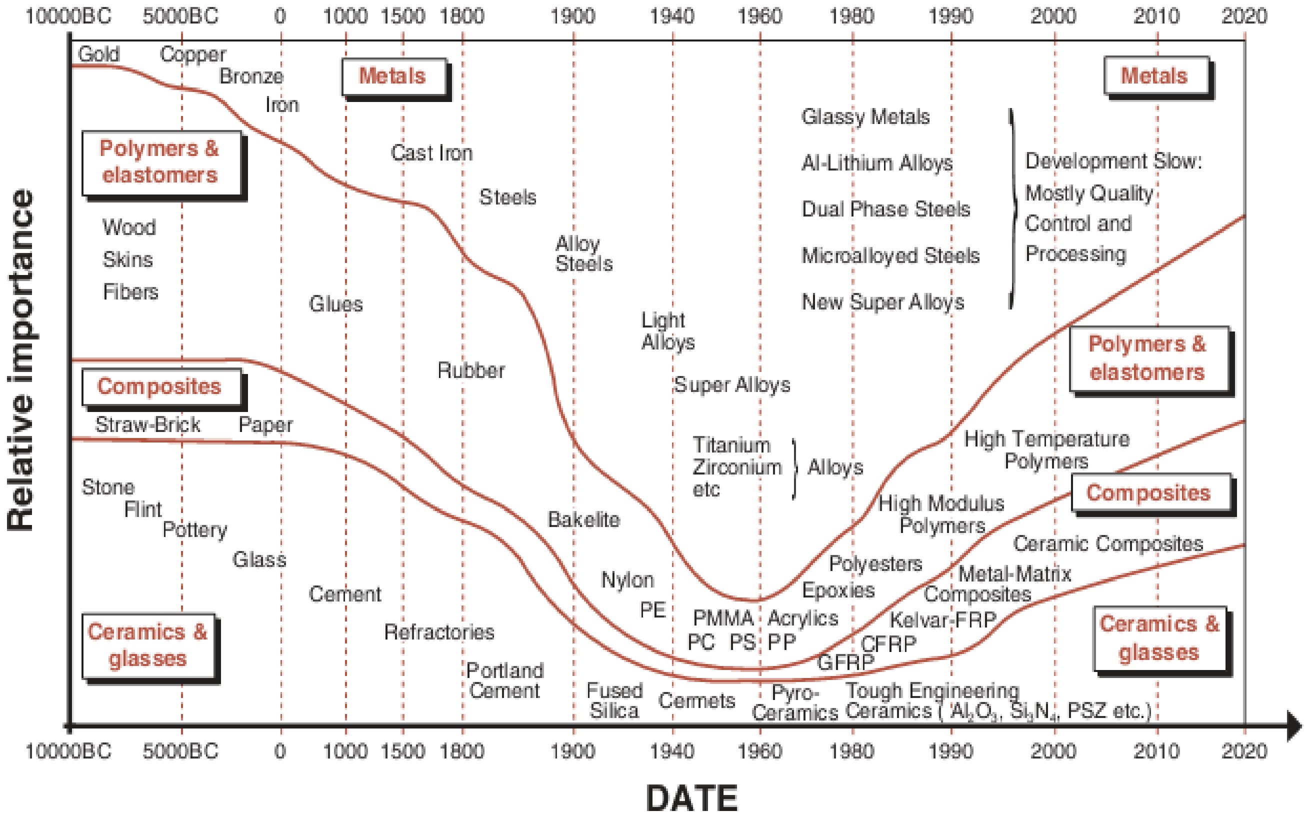


Figure 1.1 - The evolution of engineering materials with time.

1-4 - The design process:

The starting point is a market need or a new idea; the end point is the full product specification of a product that fills the need or embodies the idea.

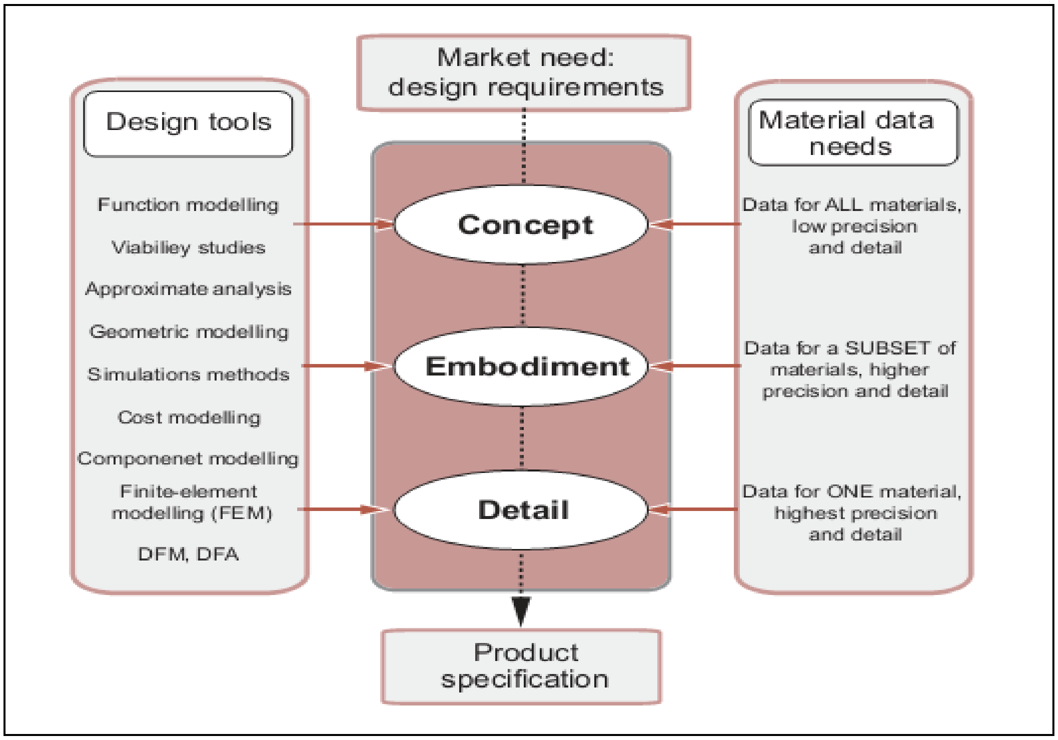


Fig. 1.2 – design process flow chart (general).

A <u>*need must be identified before it can be met.*</u> *It is essential to define the need precisely, that is,* <u>*to formulate a need statement,*</u> *often in the form: ''a device is required to perform task X'', expressed as a set of design requirements*. Writers on design emphasize that the statement and its elaboration in the design requirements should be <u>solution- neutral</u> (i.e. they 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 1.2) and (figure 1.3) : the stages of conceptual, embodiment and detailed designs, explained in a moment.

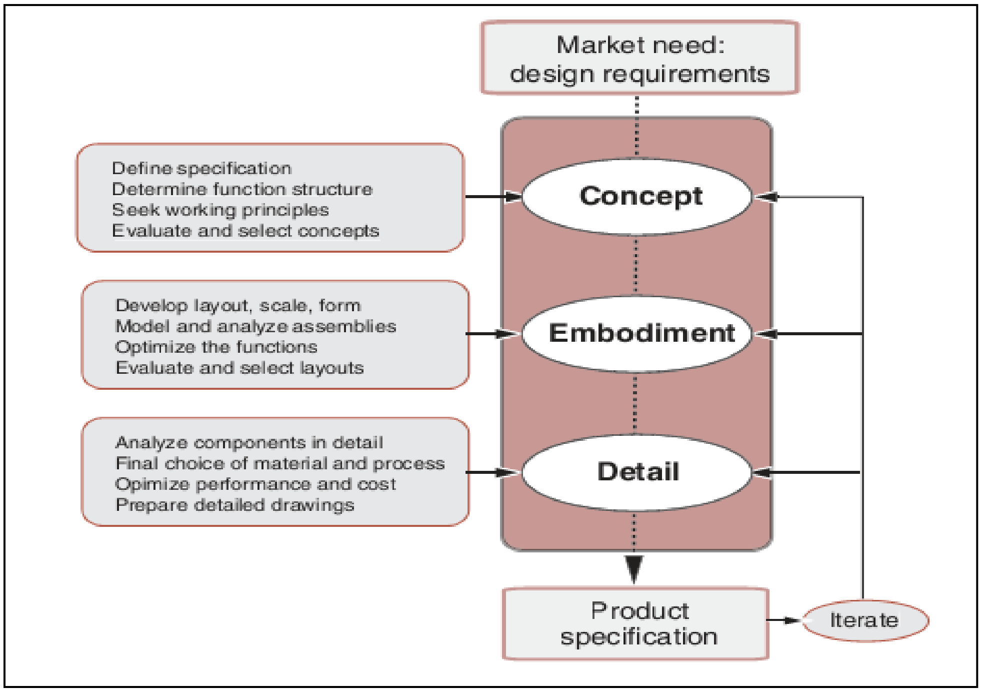


Figure 1.3 - The design flow chart. The design proceeds from the identification of a market need , clarified as a set of design requirements , through concept, embodiment and detailed analysis to a product specification .

The product itself is called a ***technical system***. A technical system *consists of sub-assemblies and components, put together in a way that performs the required task*, as in the breakdown of (Figure 1.4).

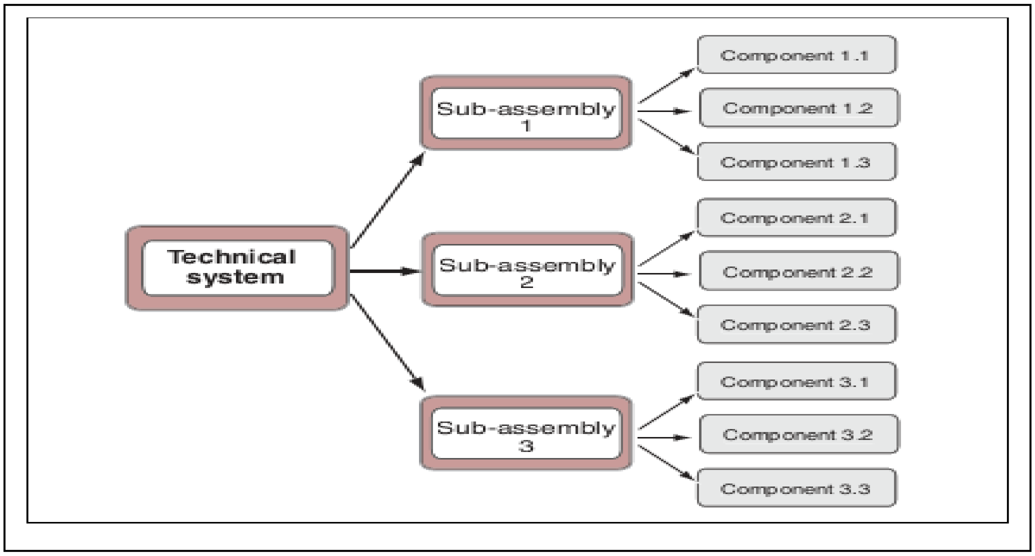


Figure 1.4- The analysis of a technical system as a breakdown into assemblies and components. Material and process selection is at the component level.

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 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 1.5. 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 sub-systems each of which performs a specific function, as in

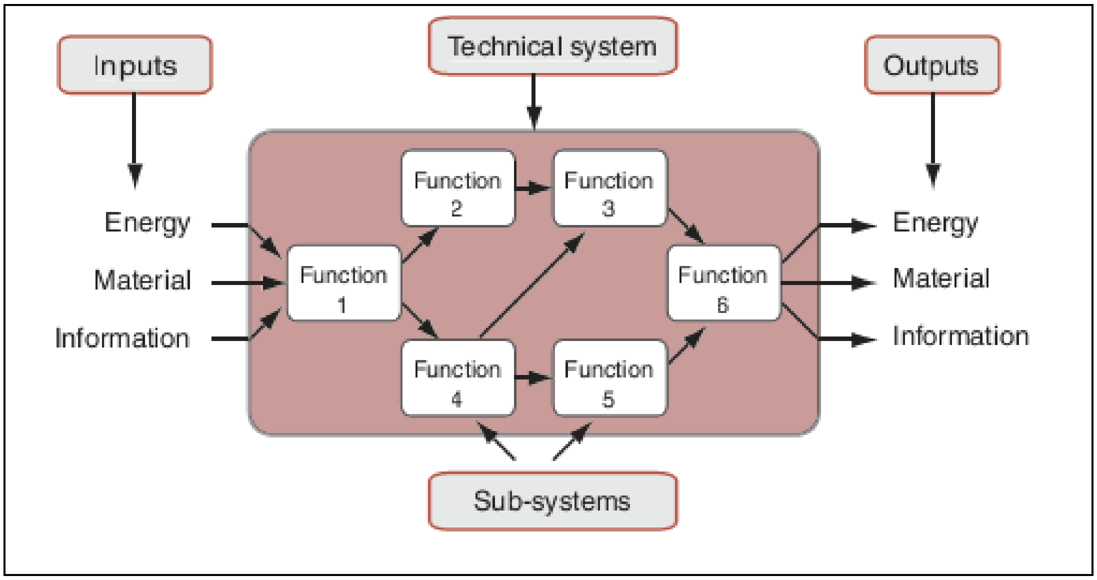


Figure 1.5 - The systems approach to the analysis of a technical system, seen as transformation of energy, materials and information (signals). This approach, when elaborated, helps structure thinking about alternative designs.

From Figure above, the resulting arrangement is called the function-structure or function decomposition of the system. 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*

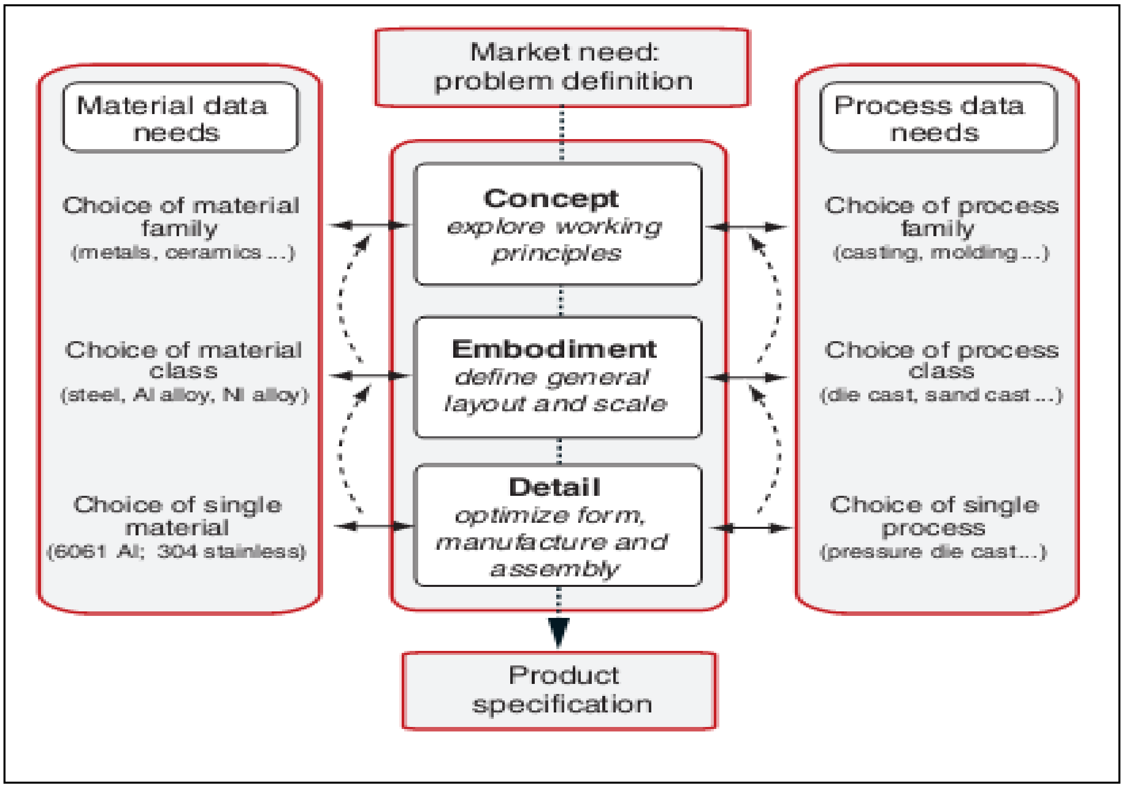
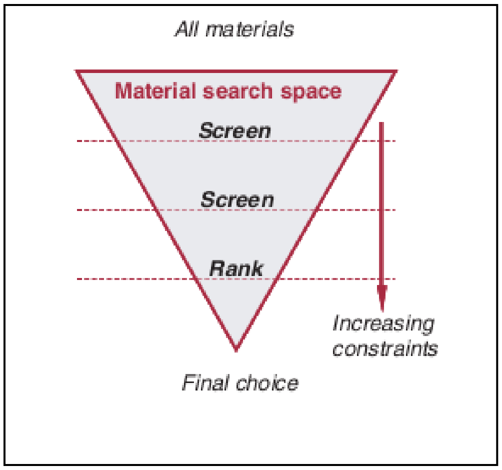


Figure 1.6 - The design flow chart, showing how material and process selection enter. Information about materials is needed at each stage, but at very different levels of breadth and precision. The broken lines suggest the iterative nature of original design and the path followed in redesign.

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 coasted. The stage ends with a detailed production specification.



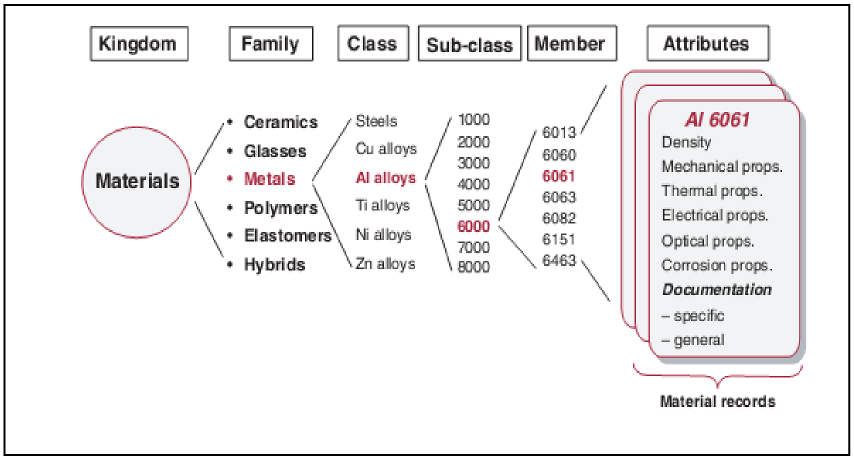


Fig.1.7 – the screening process

fig.1.8- material selected for their properties

1-5- Materials selection in the design:

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 .

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 the 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 loosing sight of the bigger spread of materials to which we must return if the details do not work out; it is easy to get trapped in a single line of thinking — a single set of ‘‘connections’’ in the sense described in the last section — when other combinations of connections offer a better solution to the design problem.

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, 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 his product used in the design calculations; that 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.

The material 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 re-selection can eliminate.

1-6 - 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, macro -shape, and —

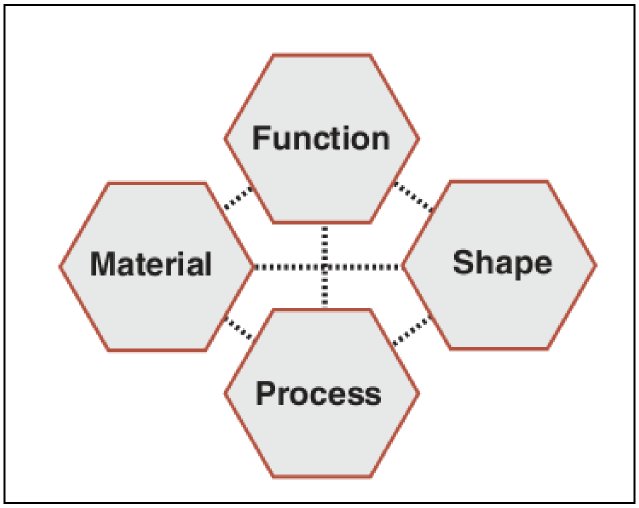


Fig. 1.9- The central problem of materials selection in mechanical design: the interaction between function, material, shape and process

when necessary — the internal, or micro-shape, as in a honeycomb or cellular structure. To make the shape, the material is subjected to processes that, 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* (e.g. welding).

Function, material, shape and process interact (Figure 1.9). 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 and the greater the interactions. The interaction between function, material, shape, and process lies at the heart of the material selection process, see (fig. 1-10). To tackle it we need a strategy.

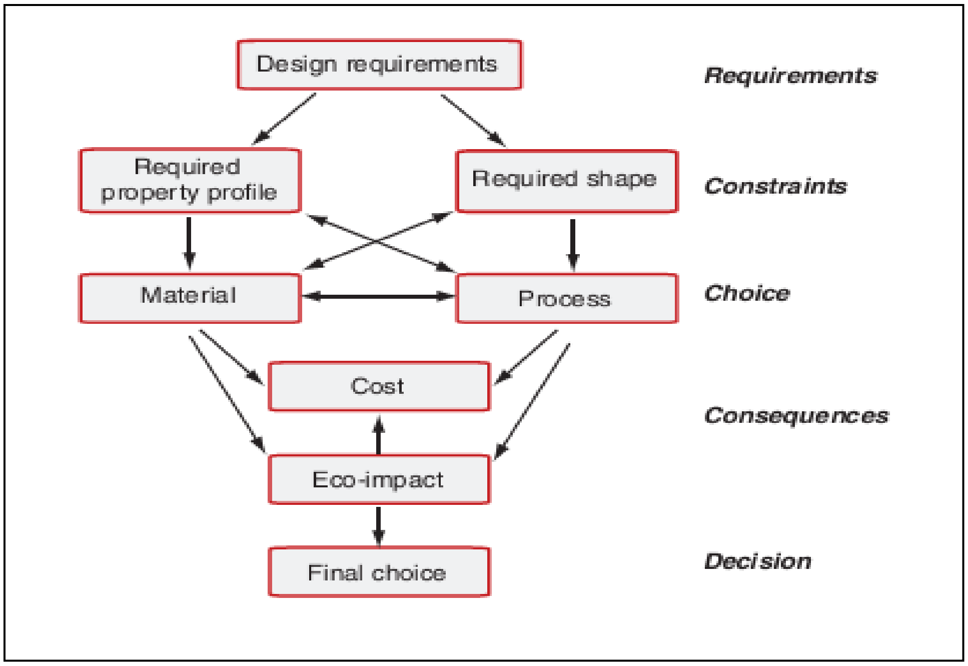


Figure 1.10 - The interaction between design requirements, material, shape and process.

1-7 - The strategy: translation, screening, ranking and documentation:

Selection involves seeking the best match between the attribute profiles of the materials and processes—bearing in mind that these must be mutually compatible—and those required by the design. The strategy, applied to materials, is sketched in Figure 1.11. The first task is that of translation: converting the design requirements into a prescription for selecting a material. This proceeds by identifying the constraints that the material must meet and the objectives that the design must fulfill. These become the filters: materials that meet the constraints and rank highly in their ability to fulfill the objectives are potential candidates for the design. The second task, then, is that of screening: eliminating the material that cannot meet the constraints. This is followed by the ranking step, ordering the survivors by their ability to meet a criterion of excellence, such as that of minimizing cost. The final task is to explore the most promising candidates in depth, examining how they are used at present, how best to design with them, case histories of failures and a step we call *documentation*.

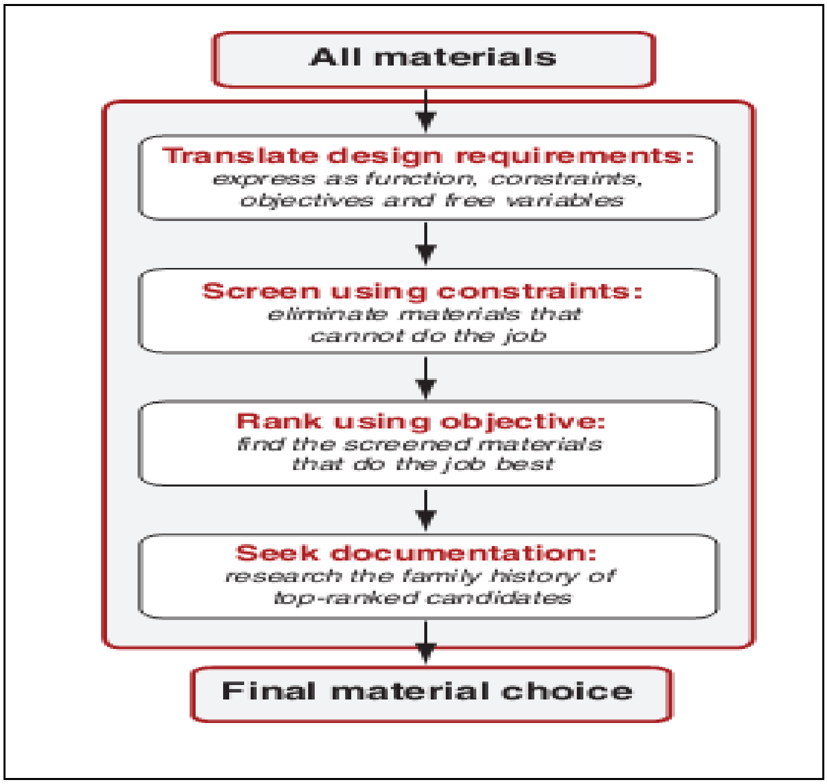


Figure 1.11 - The strategy applied to materials. The same strategy is later adapted to select processes. There are four steps: translation, screening, ranking and supporting information. All can be implemented in software, allowing large populations of materials to be investigated.

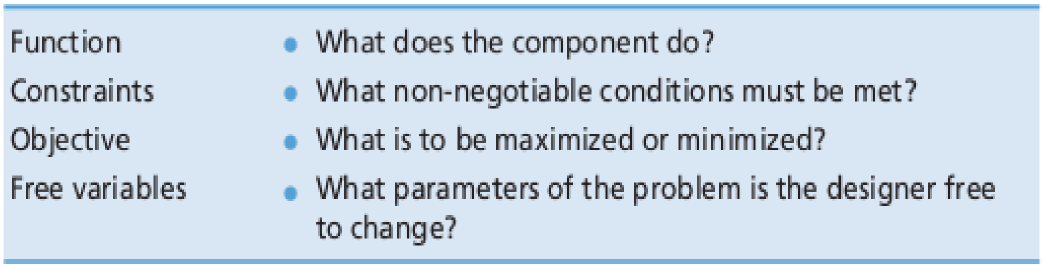
Process selection follows a parallel route. In this case translation means identifying the geometric and other constraints—dimensions, shape, precision and material compatibility—that must be met, using these to screen out processes that cannot provide them.

Translation

Any engineering component has one or more *functions*: to support a load, to contain a pressure, to transmit heat and so forth. This must be achieved subject to constraints : that certain dimensions are fixed, that the component must carry the design loads without failure, the need to insulate against or to conduct heat or electricity, that it can function in a certain range of temperature and in a given environment, and many more. In designing the component, the designer has one or more objectives: to make it as cheap as possible, perhaps, or as light, or as safe, or some combination of these. Certain parameters can be adjusted in order to optimize the objective—the designer is free to vary dimensions that are not constrained by design requirements and, most importantly, free to choose the material for the component and the process to shape it. We refer to these as *free variables*.

Constraints, objectives and free variables (Table 1.1) define the boundary conditions for selecting a material and—in the case of load-bearing components— a shape for its cross-section.

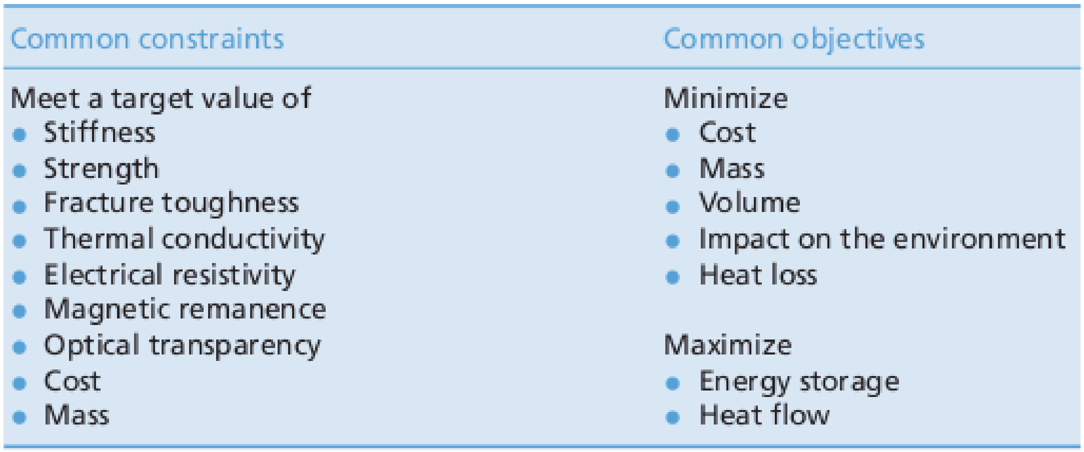
Table 1.1 Function, constraints, objectives and free variables



Function	● What does the component do?
Constraints	● What non-negotiable conditions must be met?
Objective	● What is to be maximized or minimized?
Free variables	● What parameters of the problem is the designer free to change?

It is important to be clear about the distinction between constraints and objectives. A constraint is an essential condition that must be met, usually expressed as a limit on a material or process attribute. An objective is a quantity for which an extreme value (a maximum or minimum) is sought, frequently cost, mass or volume, but there are others (Table 1.2). Getting it right can take a little thought.

Table 1.2 Common constraints and objectives



Common constraints	Common objectives
Meet a target value of	Minimize
• Stiffness	• Cost
• Strength	• Mass
• Fracture toughness	• Volume
• Thermal conductivity	• Impact on the environment
• Electrical resistivity	• Heat loss
• Magnetic remanence	
• Optical transparency	Maximize
• Cost	• Energy storage
• Mass	• Heat flow

In choosing materials for a super-light sprint bicycle, for example, the objective is to minimize mass, with an upper limit on cost, thus treating cost as a constraint. But in choosing materials for a cheap ‘shopping’ bike the two are reversed: now the objective is to minimize cost with a (possible) upper limit on mass, thus treating it as a constraint (Figure 1.12).

The outcome of the translation step is a list of the design-limiting properties and the constraints they must meet. The first step in relating design requirements to material properties is therefore a clear statement of function, constraints, objectives and free variables.

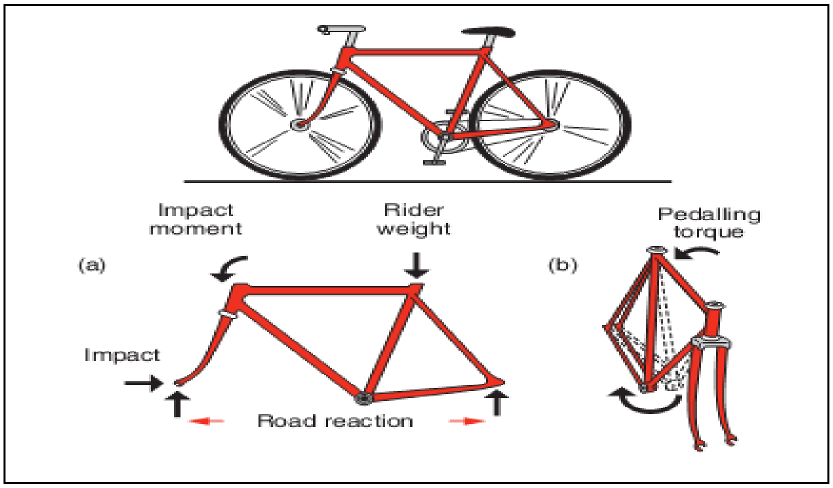


Fig.1.12

Screening

Constraints are gates: meet the constraint and you pass through the gate, fail to meet it and you are out. Screening (Figure 1.11) does just that: it eliminates candidates that cannot do the job at all because one or more of their attributes lies outside the limits set by the constraints. As examples, the requirement that ‘the component must function in boiling water’ or that ‘the component must be transparent’ imposes obvious limits on the attributes of maximum service temperature and optical transparency that successful candidates must meet. We refer to these as attribute limits.

Ranking

To rank the materials that survive the screening step we need a criterion of excellence. They are found in the material indices, which measure how well a candidate that has passed the screening step can do the job (Figure 1.11). Performance is sometimes limited by a single property, sometimes by a combination of them. Thus, the best materials for buoyancy are those with the lowest density, **ρ**; those best for thermal insulation are the ones with the smallest values of the thermal conductivity, **λ**—provided, of course, that they also meet all other constraints imposed by the design. Here maximizing or minimizing a single property maximizes performance. Often, though, it is not one but a group of properties that are relevant. Thus, the best materials for a light stiff tie-rod are those with the greatest value of the specific stiffness, **E/ρ**, where E is Young’s modulus. The best materials for a spring are those with the greatest value of **σ^2 Y /E**, where σy is the yield strength. *The property or property group that maximizes performance for a given design is called its* ***material index***. There are many such indices, each associated with maximizing some aspect of performance. They provide criteria of excellence that allow ranking of materials by their ability to perform well in the given application.

To summarize: screening isolates candidates that are capable of doing the job; ranking identifies those among them that can do the job best.

Documentation

The outcome of the steps so far is a ranked short-list of candidates that meet the constraints and that maximize or minimize the criterion of excellence, whichever is required. You could just choose the top-ranked candidate, but what hidden weaknesses might it have? What is its reputation? Has it a good track record?

To proceed further we seek a detailed profile of each: its documentation (Figure 1.11, bottom). What form does documentation take? Typically, it is descriptive, graphical or pictorial: case studies of previous use of the material, details of its corrosion behavior in particular environments, of its availability and pricing, warnings of its environmental impact or toxicity. Such information is found in handbooks, suppliers' data sheets, CD-based data sources and high-quality Websites. *Documentation helps narrow the short-list to a final choice, allowing a definitive match to be made between design requirements and material and process attributes.*

Why are all these steps necessary? Without screening and ranking, the candidate pool is enormous and the volume of documentation is overwhelming. Dipping into it, hoping to stumble on a good material, gets you nowhere. But once a small number of potential candidates have been identified by the screening –ranking steps, detailed documentation can be sought for these few alone, and the task becomes viable.

Case study: Devices to open corked bottles

When you buy a bottle of wine you find, generally, that it is sealed with a cork. This 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 allow access to wine in a corked bottle' and might add, 'with convenience, at modest cost, and without contaminating the wine'. Three concepts for doing this are shown in (Figure 1.14). In order, they are: to remove the cork by axial traction (pulling); to remove it by shear tractions; to push it out from below. 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 1.15, shows embodiment sketches for devices based on concept (a), 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 suggest the layout, the mechanisms and the scale. In the final, detailed, stage of design, the components are dimensioned so that they carry the working loads safely, their precision and surface finish are

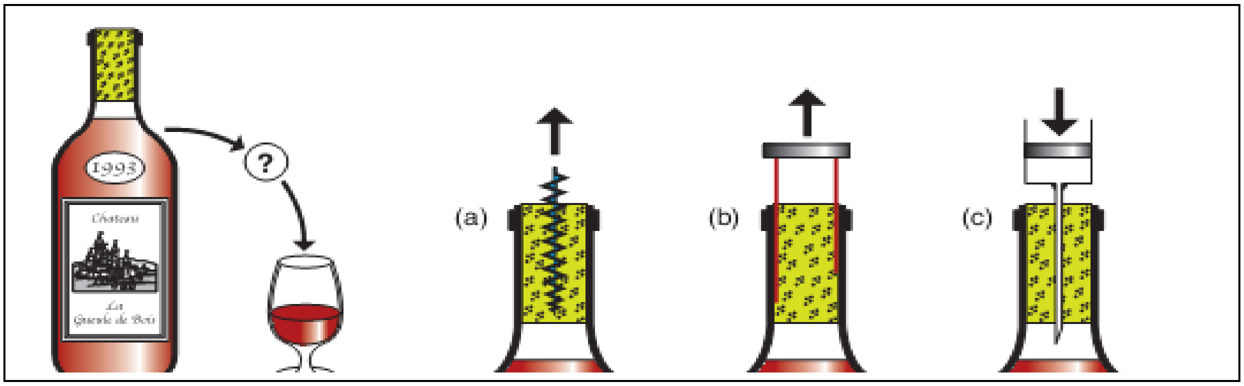


Figure 1.14- shows embodiment sketches for devices based on concept

defined, and a final choice of material and manufacturing route is made as suggested on the right of the figure.

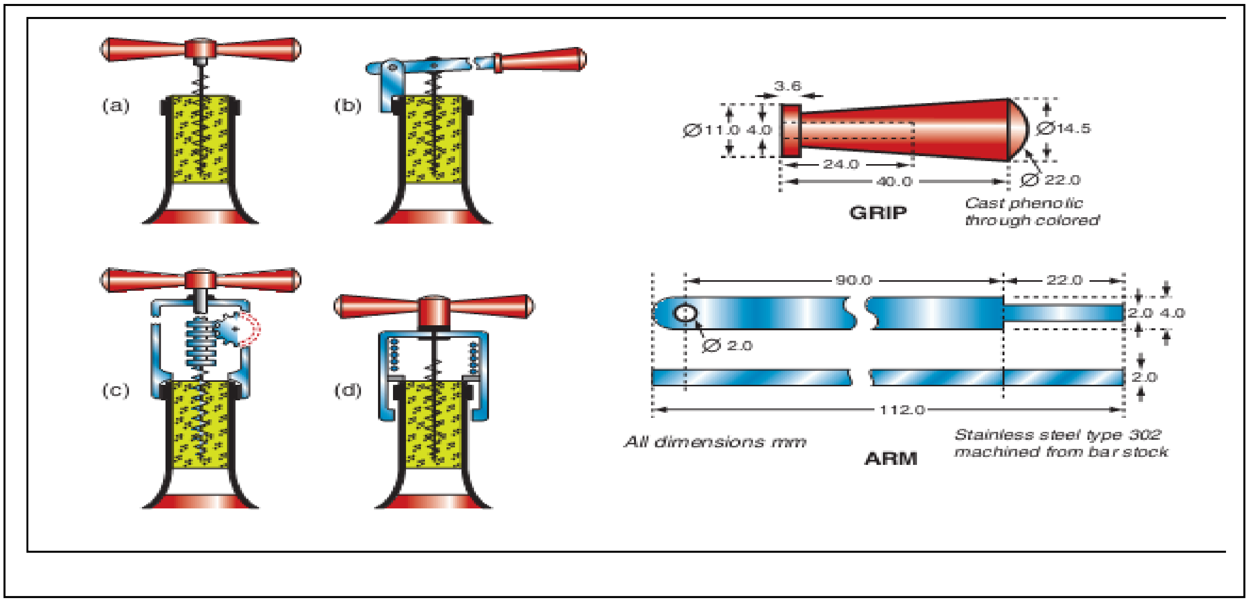


Figure 2.7- Embodiment sketches for the first concept: direct pull, levered pull, geared pull and spring-assisted pull. Each system is made up of components that perform a sub- function. Detailed design drawings for the lever of embodiment (b) are shown on the right

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