Chapter 3
Strategic thinking: matching material to design

3.1 Introduction and synopsis

- Develop a design-led approach to materials selection.
- Briefly review the design process. A *market need* leads to *design requirements* and *product specifications*. Choice of materials and processes evolves in parallel.
- Selection strategy: *translation*, *screening*, *ranking*, *documentation*.

3.2 The design process

- Starting point: market need or new idea
  End point: full product specification
- Critical to have a precise need statement expressed as a set of design requirements.
- Stages:

  conceptual design (all options are considered)

  embodiment (**concretisering**, most promising concepts are analyzed approximately – preliminary sizing, selection, performance, and cost)

  detailed design (detailed specifications, analysis, optimization, final choices, detailed product specification)
- Design can be *original* (new idea or working principle, often stimulated by new materials with improved properties) or *redesign* (improving an existing product) driven by failures, poor relative performance, low profit, new ‘editions’).

Examples

- New idea or working principle

Vinyl audio record
Cassette tape
Compact disc
MP3 player

- New material with improved properties

Material	Application
High-purity silicon	Transistor → all of ict
High-purity glass	Optical fiber
High-coercivity magnets	Miniature earphone
Solid-state lasers	CD, DVD
New radiation-resistant alloys	Nuclear technology
New lightweight composites	Space technology
High-temperature materials	Turbine technology

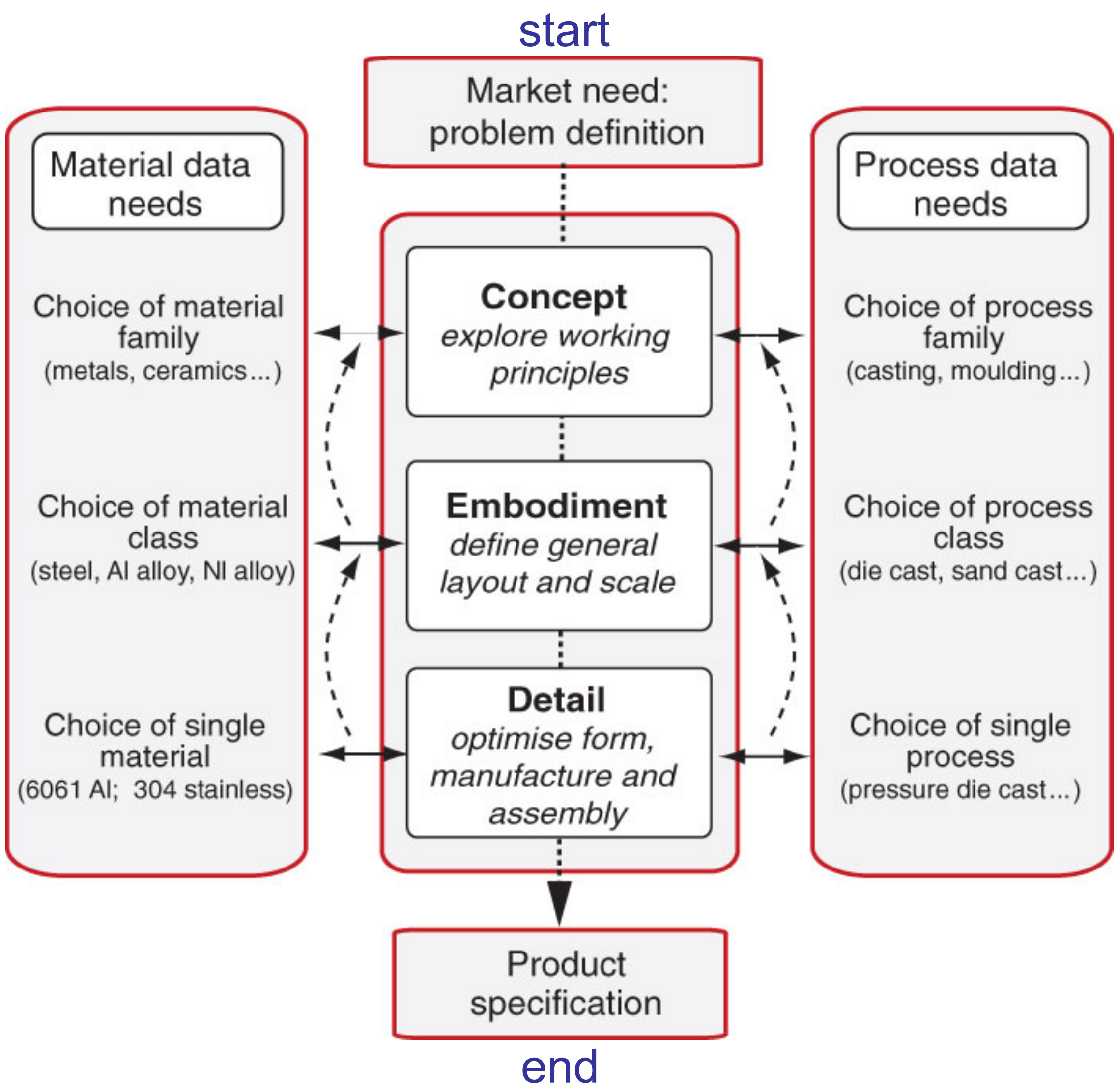
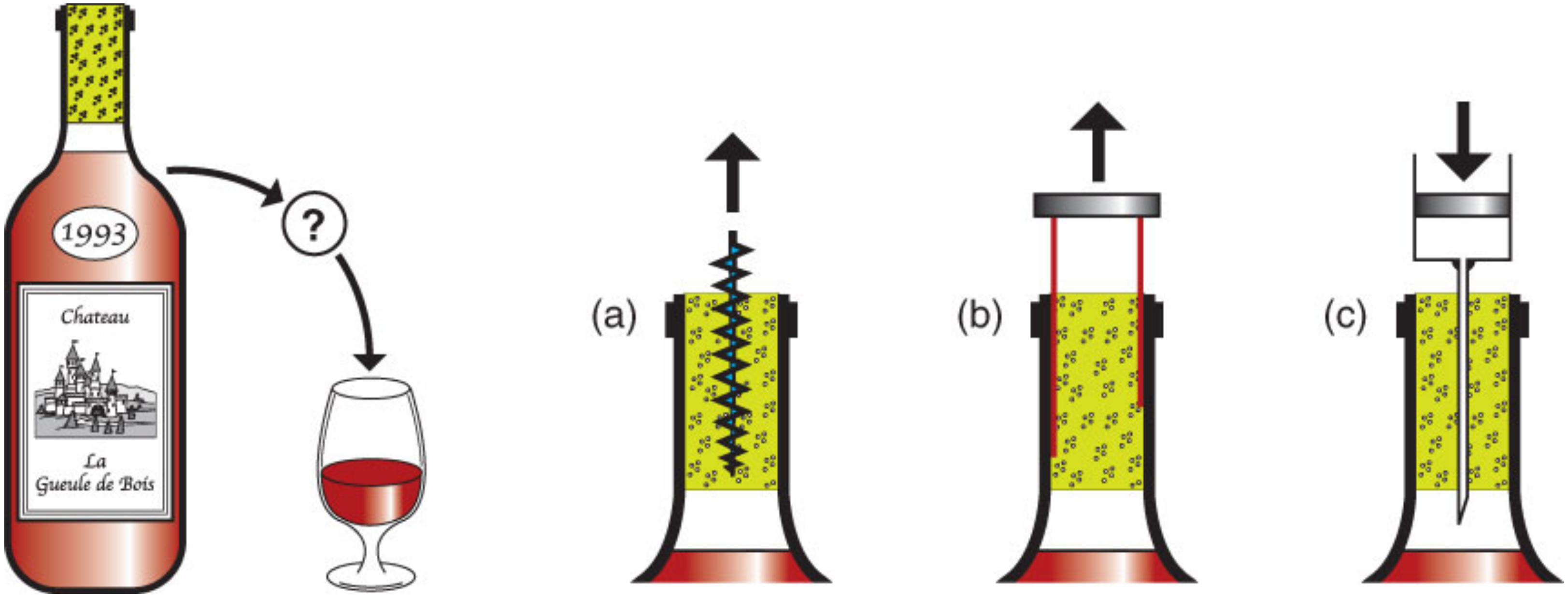


Figure 3.1 The design flow chart, showing how material and process selection enter. Information about materials is needed at each stage, but at very different levels of breadth and precision. The broken lines suggest the iterative nature of original design and the path followed in redesign.

Example



a) Axial traction – pulling via threaded screw
b) Shear traction – elastic blades
c) Pushed from below – gas pressure via hollow needle

Figure 3.2 A market need — that of gaining access to wine in corked (**corked?**) bottles — and three concepts for meeting the need. Devices based on all three of these concepts exist and can be bought.

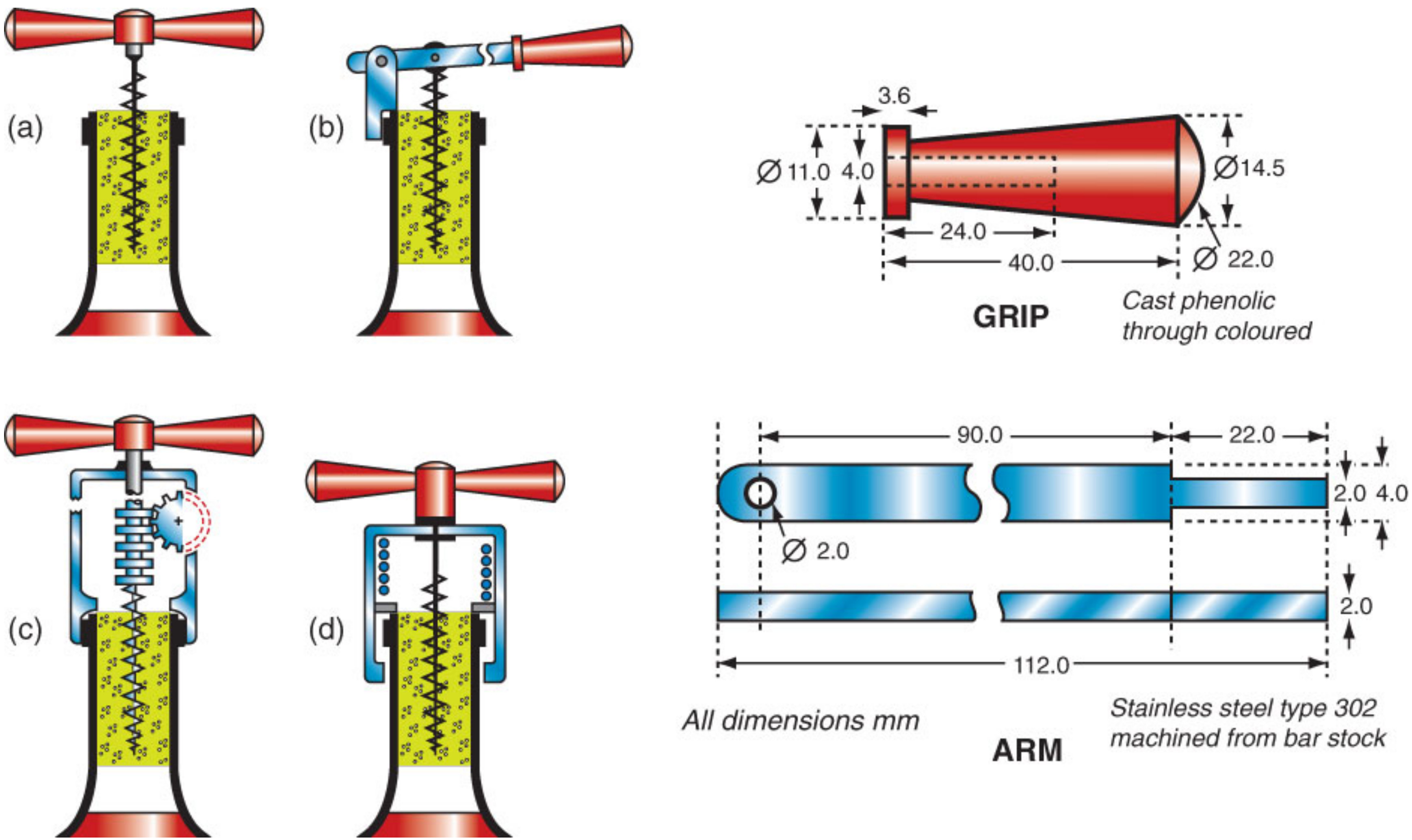


Figure 3.3 Embodiment sketches for the first concept: direct pull, levered pull, geared pull and spring-assisted pull. Each system is made up of components that perform a sub-function. Detailed design drawings for the lever of embodiment (b) are shown on the right.

3.3 Material and process information for design

- Materials selection enters each stage of the design: approximate in the concept stage, more detailed in the embodiment, and most precise in the detailed design stage.
- We narrow the materials search space by screening out unsuitable choices, ranking the remainder, and selecting the most promising.
- Material selection must be linked to process and final form or shape. Process selection runs parallel to material selection. Process choice is influenced by material, shape, and cost.
- The interaction between material, shape, and process is the core of materials selection.

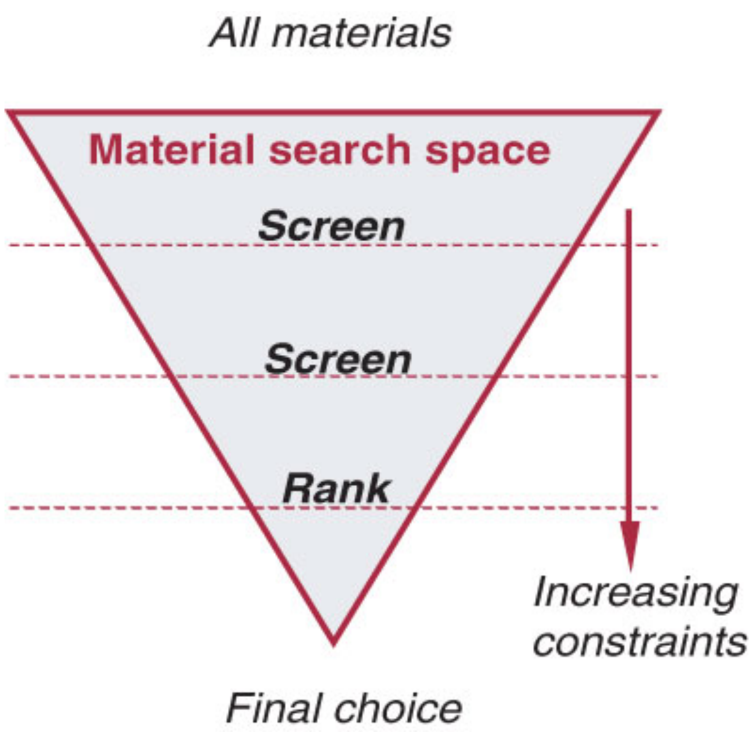


Figure 3.4 The narrowing of material search space as design constraints are applied.

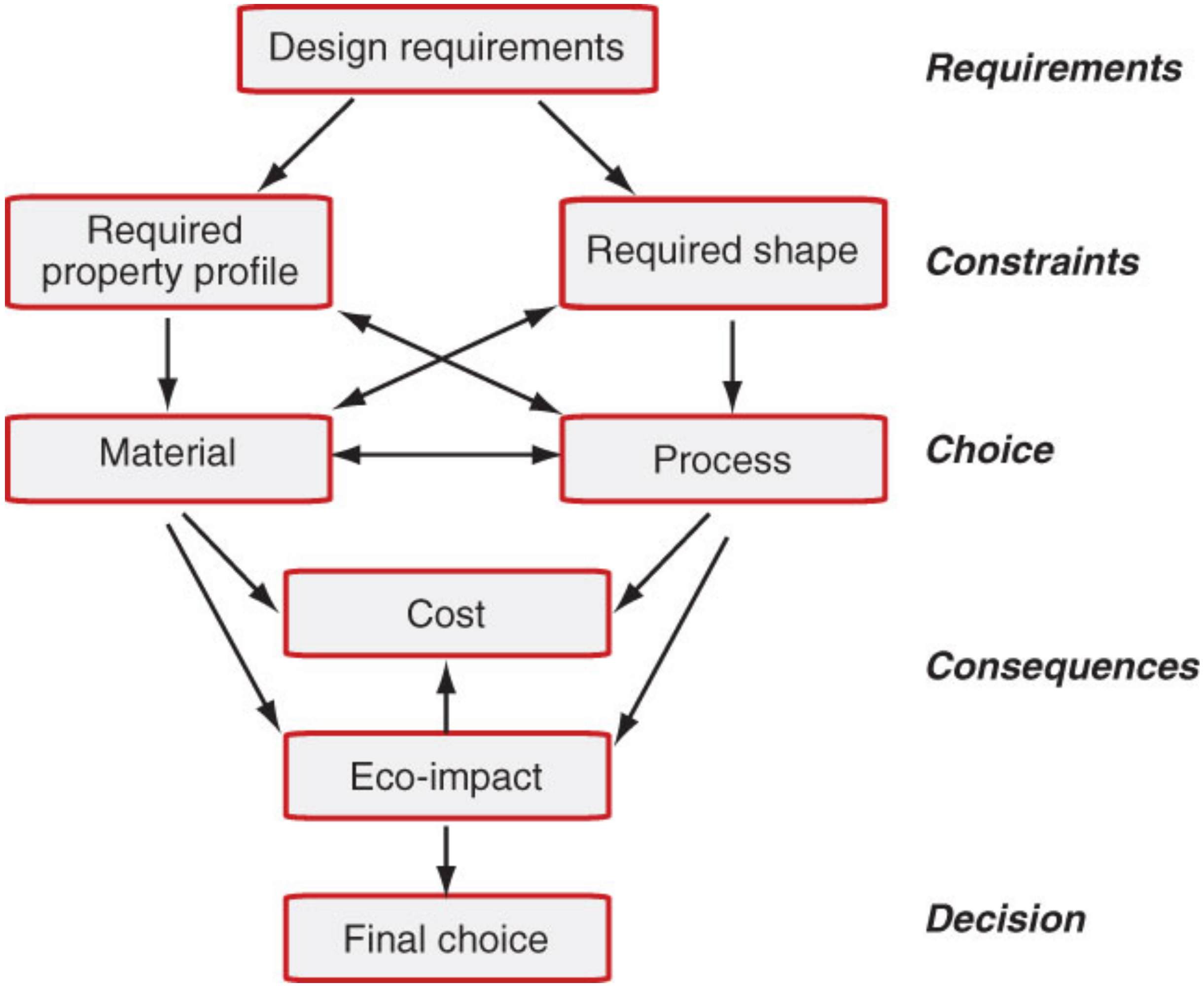


Figure 3.5 The interaction between design requirements, material, shape and process.

3.4 The strategy: translation, screening, ranking, and documentation

- *Translation*: converting design requirements into a prescription for selecting materials. Identify the constraints that must be met and the objectives the design must fulfill (filters).
- *Screening*: eliminating materials that cannot meet the constraints.
- *Ranking*: ordering by ability to meet a criterion of excellence (e.g., cost).
- *Documentation*: final assessment based on factors such as case studies, availability, pricing, environmental impact, etc.
- Process selection follows a parallel route.

Table 3.1 Function, constraints, objectives and free variables

- *Translation*: identify the key functions, constraints, objectives, and free variables of the design problem.

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

Table 3.2 Common constraints and objectives

- Common constraints: target values for stiffness, strength, fracture toughness, thermal conductivity, electrical resistivity, magnetic remanence, optical transparency, cost, mass.
- Common objectives: minimize cost, mass, volume, environmental impact, heat loss; maximize energy storage, heat flow.

- *Screening*: a gate (meet the constraint and you pass through); attributes that candidates must meet are called *attribute limits*.

- *Ranking* the survivors of the screening step requires criteria of excellence (*material indices*). Performance is sometimes limited by a single property, sometimes by a combination.

- The property or property group that maximizes performance for a given design is called its *material index.* Examples: best material for a light tie-rod has maximum E/ρ, best for a spring has maximum σ_y^2/E (as we will see later)

- *Documentation*: final assessment based on factors such as case studies, track record, availability, pricing, environmental impact, etc.

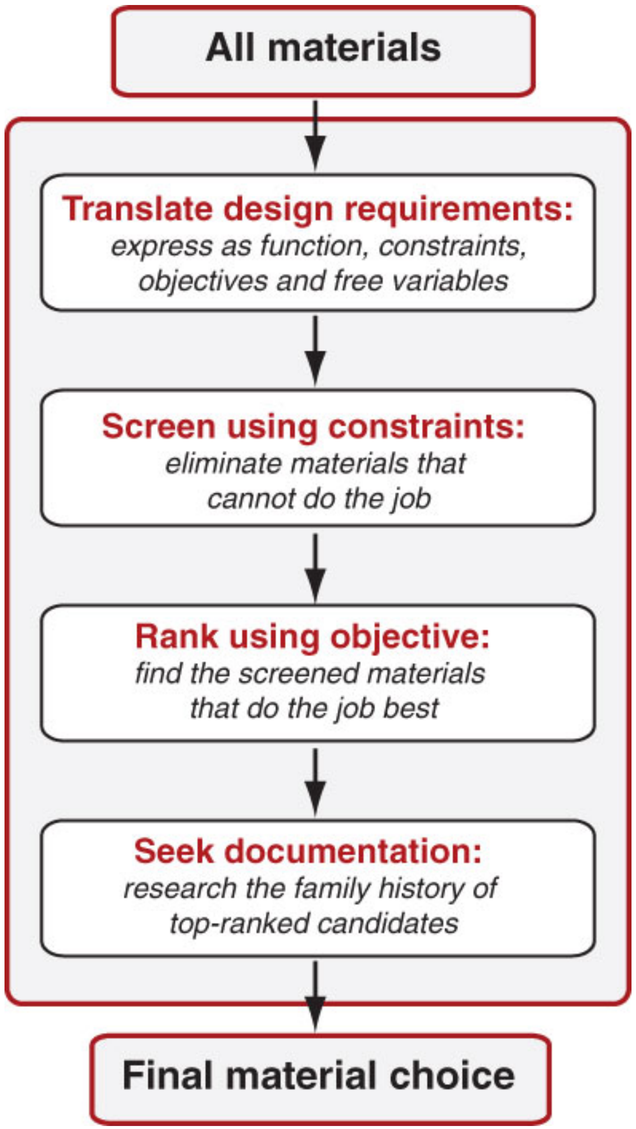
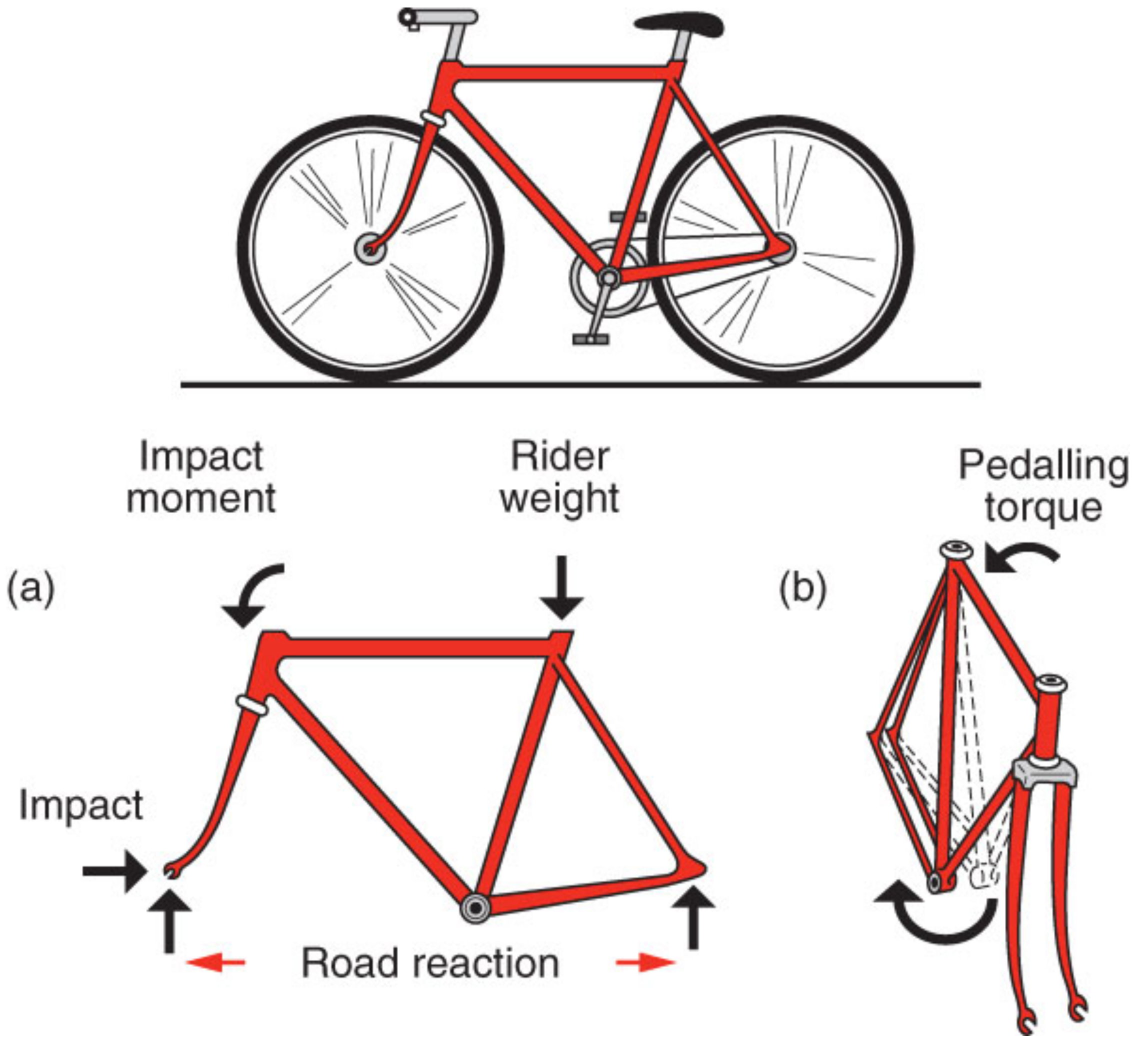


Figure 3.6 The strategy applied to materials. The same strategy is later adapted to select processes. There are four steps: translation, screening, ranking and supporting information. All can be implemented in software, allowing large populations of materials to be investigated.

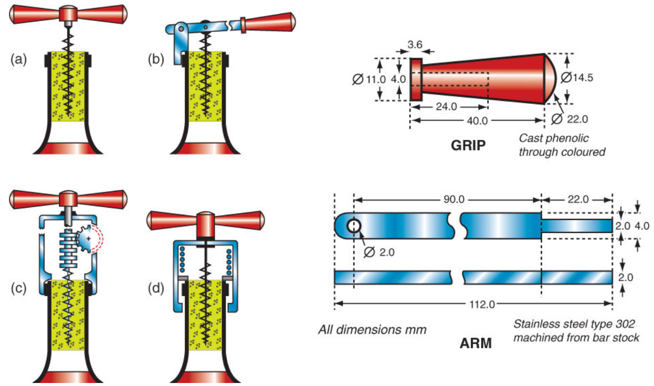


Importance depends on bicycle type
Minimize mass
Maximize strength
Maximize stiffness
Minimize cost

Figure 3.7 A bicycle. The forks are loaded in bending.

3.5 Examples of translation

Corkscrew lever (Table 3.3)



- Function – lever (beam loaded in bending)

- Constraints – functional: stiff enough, strong enough, some toughness, corrosion resistant; geometric: length L specified.

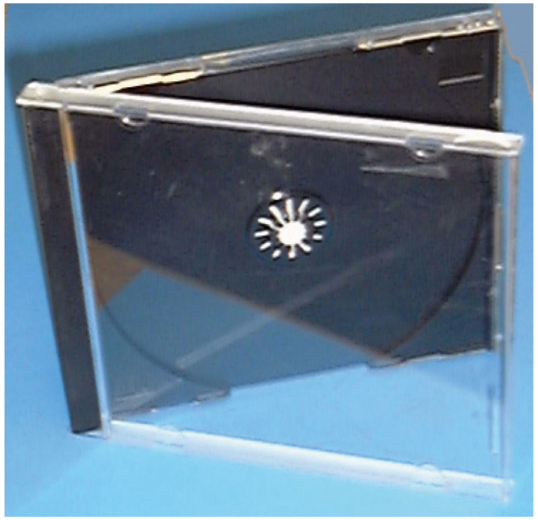
- Objective – minimize cost

- Free variables – choice of materials, choice of cross sectional area.

- The *design limiting properties* are those directly related to the constraints.

PI question

E 1.9. The cases in which most CDs are sold have an irritating way of cracking and breaking. Which design-limiting property has been neglected in selecting the material of which they are made?



1. Fracture toughness
2. Hardness
3. Strength
4. Stiffness

Redesign of a CD case (Table 3.4)

- Current technology: polystyrene (PS); cheap, clear, injection moldable, in principle recyclable; but: crack easily, broken hinges, sharp edges.
- Challenge: keep good qualities and improve the fracture toughness.

- Function – contain and protect a CD
- Constraints – optically clear, injection moldable, recyclable, tougher than PS, same dimensions as before.
- Objective – minimize cost
- Free variables – choice of material.

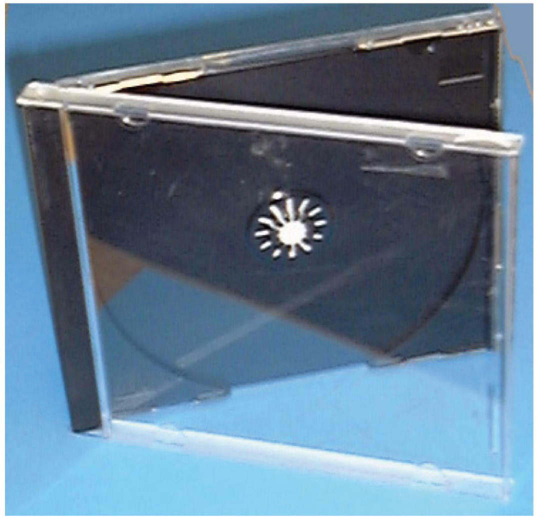


Figure 3.8 A polystyrene CD case. It is cheap, but it is brittle and cracks easily.

3.5 Examples of translation

Heat sinks for microchips (Table 3.5)

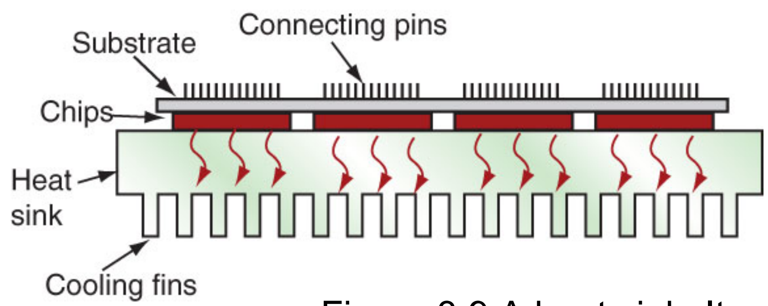


Figure 3.9 A heat sink. It must conduct heat well, but be electrically insulating.

- As chips shrink the power density increases and heating becomes a problem (~ 180°C). To prevent electrical coupling and stray capacitance the sink must be an electrical insulator and it must work continuously at 180°C. It must have the highest possible thermal conductivity.

- Function – heat sink
- Constraints – good electrical insulator, high operating temperature, dimensions are specified
- Objective – maximize thermal conductivity
- Free variables – choice of material

3.5 Examples of translation

HF transformer cores (Table 3.6)

- Uses electromagnetic induction to convert one AC voltage to another. Must be a soft magnet to minimize energy loss and an electrical insulator to avoid eddy current losses at high frequencies.

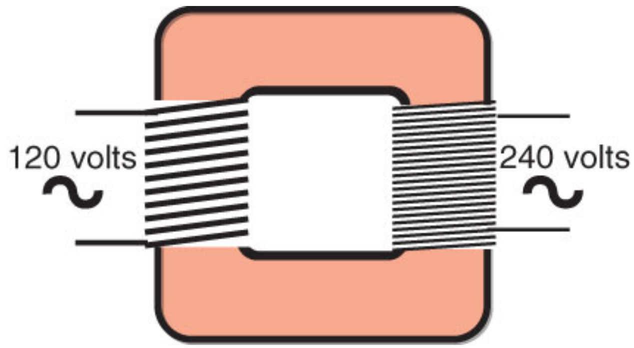


Figure 3.10 A transformer. The core must be a soft magnetic material, and if this is a high-frequency transformer, it must be an electrical insulator.

- Function – HF transformer core
- Constraints – soft magnet, electrical insulator, dimensions specified
- Objective – minimize cost
- Free variables – choice of material

Exercise

E 3.6. A material is required for the windings of an electric air-furnace capable of temperatures up to 1000 ºC. Think out what attributes a material must have if it is to be made into windings and function properly in a furnace. List the function, the constraints, the most probable objective and the free variables.