

Material Selection Criteria

In designing a structure or device, an engineer has a vast range of materials to choose from. How are the materials used selected? The materials used are chosen for a variety of reasons, including;

Price and availability	}	Economic Properties
Density		
Modulus and damping	}	Bulk mechanical Properties
Yield strength, tensile strength, hardness		
Fracture toughness		
Fatigue strength, thermal fatigue resistance		
Creep strength		
Thermal properties	}	Bulk non-mechanical properties
Optical properties		
Magnetic properties		
Electrical properties		
Oxidation and corrosion	}	Surface properties
Friction, abrasion and wear		
Ease of manufacture, Fabrication, joining, finishing	}	Production properties
Appearance, texture, feel		
		Aesthetic properties

In addition to these properties, the following may also influence the choice of material used;

Consumer confidence and expectations

Environment and recyclability

Logistics

Marketing

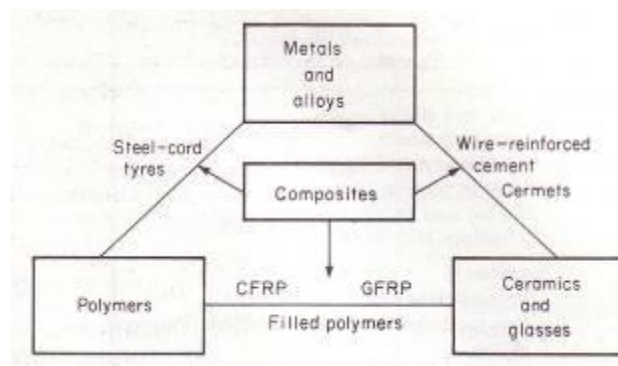
Legislation

Health and safety

Many of these factors are closely linked to each other, for example density and logistic costs, the environment and legislation.

The types of materials that are available to a designer are shown below;

Metals and alloys
Iron and steels
Aluminium and its alloys
Copper and its alloys
Nickel and its alloys
Titanium and its alloys
Polymers
Polyethylene (PE)
Polymethylmethacrylate (PMMA, Perspex)
Nylon
Polystyrene (PS)
Polyurethane (PU)
Polyvinylchloride (PVC)
Rubbers
Ceramics and glasses*
Alumina (Al_2O_3 , emery, sapphire)
Magnesia (MgO)
Silica (SiO_2) glasses and silicates
Silicon carbide (SiC)
Silicon nitride (Si_3N_4)
Cement and concrete
Composites
Wood
Fibreglass (GFRP)
Carbon-fibre reinforced polymers (CFRP)
Filled polymers
Cermets



Let's consider the simple example of a plastic-handled screwdriver, and consider the choices that the engineer would make during the development. Our screwdriver has a shaft and a blade made of high-carbon steel and a handle made of polymethylmethacrylate (Perspex or PMMA).

Bulk Mechanical Properties. To achieve its function the screwdriver must be able to resist torsion with very little twist and hence the shaft should have a high elastic modulus. The shaft must also have a high yield stress, otherwise when large torques are transmitted it will permanently deform. The blade must have high hardness, otherwise it will be indented by the material of the head of the screw. Finally the material must also resist fracture, so that if it does exceed yield it will plastically deform rather than fracture which would be dangerous to the user.

Production Properties. The handle of the screwdriver has a larger diameter so the stresses seen in the handle are much less than those seen in the shaft and hence the elastic modulus is less important. Due to the fact that PMMA becomes soft when heated it is very easy to mould into its final shape and hence cheap.

Bulk non-mechanical properties. If the screwdriver were to be used by electricians then the fact that the handle is an insulator would be important and so influence the material choice.

Economic Properties. The material cost of the PMMA is cheap and in high volumes, it is cheap to process.

Surface Properties. If the shaft were to be made of a stainless steel then the shaft would also have improved resistance to corrosion.

Aesthetic Properties. A plastic handle has the right appearance, feel and texture that a consumer would expect.

Often it is price that is the overriding factor that influences material choice rather than mechanical properties. The table below shows a rough breakdown of costs;

		Price per tonne
Basic construction	Wood, concrete, structural steel	UK£30–250, US\$60–550
Medium and light engineering	Metals, alloys and polymers for aircraft, automobiles, appliances, etc.	UK£250–2500, US\$550–5500
Special materials	Turbine-blade alloys, advanced composites (CFRP, BFRP), etc.	UK£2500–90,000, US\$5500–200,000
Precious metals, etc.	Sapphire bearings, silver contacts, gold microcircuits	UK£90,000–1 m, US\$200,000–2.2 m
Industrial diamond	Cutting and polishing tools	UK£400 m, US\$900 m

The function of the component and the value added to the product dictate the cost that a manufacturer is willing to pay for the material that the component is made from. For example;

Large scale use. Materials that are readily available, used in large quantities, and add little value to the product such as wood, cement and concrete have low costs associated with them. There are other materials that have all the required properties to achieve the same function, but their use in these sorts of applications is eliminated by their high price.

Light – medium engineering use. If a component adds some value to the finished product then the economic constraint of the material choice is less severe – a far greater proportion of the cost of the structure is that associated with labour or with production and fabrication. It is in this sector of the market that the competition between materials is most intense – polymers, ceramics and composites compete directly with metals.

High performance applications. In a high performance application a material may be used that is more expensive, but adds more value to the product. For example, the use of Carbon Fibre Reinforced Plastic (CFRP) in high performance and race vehicles, where the advantages of weight and stiffness are seen as worthwhile benefits over the associated increase in cost.

Precious metals and gemstones. Are used in specialist applications where the material properties are vital for the functionality of the component. For example, industrial diamonds that are used for cutting tools.

Other things that influence the decision for material choice may not involve mechanical properties or cost. For example

- a supplier trying to sell components to an automotive manufacturer in a new material must give the manufacture confidence in the new material.
- A consumer may be influenced by marketing to buy a product due to its material and its perceived benefits even if these do not exist.
- If a part is manufactured a long way from its final market, logistics costs may contribute significantly to the price of the product. If the material choice means that the part is lighter or can be transported at a lower cost this may also be considered.

- With increased awareness of environmental change consumers and legislation may demand that materials used are environmentally friendly, consume less energy to manufacture and produce and can be recycled.
- A particular industry may have legislations that have to be adhered to that may influence material choice, for example the aerospace industry has stringent flammability tests that must be passed before a material is allowed to be used.
- Health and safety factors govern such items as fuel tank integrity, windscreen vision, exhaust emissions, asbestos free friction materials and solvent/water based paints.
- Disposal methods, the cost of landfill and the economic and environmental necessity of recycling.

Price and Availability of materials

As already discussed the price of materials can significantly influence their usage. Not only the relative cost of materials to each other, but also the cost of a material over time. For example, a sample of material costs for different materials over time is shown below;

	Current	6 months ago	12 months ago
Chromium, lump/UK£ (US\$) tonne ⁻¹	3500 (7700)	3200 (7040)	2900 (6380)
Copper, cathodes/UK£ (US\$) tonne ⁻¹	1052 (2314)	926 (2037)	764 (1680)
Gold/US\$ Troy oz ⁻¹	610	251	222
Lead, refined pig/UK£ (US\$) tonne ⁻¹	437 (961)	578 (1270)	428 (942)
Mercury/US\$ Flask ⁻¹	390	300	127
Nickel, refined/UK£ (US\$) tonne ⁻¹	3196 (7031)	2675 (5885)	2169 (4772)
Tungsten, powder/UK£ (US\$) kg ⁻¹	11.8 (26.0)	12.8 (28.2)	13.5 (29.7)

This sample highlights two important points;

There is a long term upwards movement in material costs. Twenty years prior to the above sample, copper was £200/tonne and lead was £110/tonne, in the above sample they are more than four times this price. This reflects, in part, the real cost (capital investment, labour and energy) of extracting and transporting the raw material and processing it to give the engineering material. Inflation and increased energy costs obviously drive the price up; so too, does the necessity to extract materials, like copper, from increasingly lean ores.

There can be large short term fluctuations in material costs. In the above sample, lead has dropped in price by 30% in 6 months and in the same period gold has risen by 140%. Nickel has risen by 47% in 12 months, yet in the 12 months previous, it had fallen by 40%. These significant fluctuations have little to do with real scarcity or abundance of materials, but instead are due to small differences in supply and demand. They can also be due to political factors – a scarcity, and hence increase in price, of cobalt in 1978 was due to the guerilla attacks on mineworkers in Zaire, the world's principle producer of cobalt. The twin towers resulted in an immediate increase in fuel costs.

In the long term it is therefore important to know which materials are plentiful, which are scarce and which are in demand. The table shows the UK imports of engineering materials as a percentage of total cost.

Iron and steel	27
Wood and lumber	21
Copper	13
Plastics	9.7
Silver and platinum	6.5
Aluminium	5.4
Rubber	5.1
Nickel	2.7
Zinc	2.4
Lead	2.2
Tin	1.6
Pulp/paper	1.1
Glass	0.8
Tungsten	0.3
Mercury	0.2
Etc.	1.0

Looking at figures like the ones above give us some indication as to which materials are in demand. To understand which materials are available we need to consider the abundance of the material and the cost of processing that material from its raw ingredients into a form that can be used. The table below shows the abundance of elements by weight as a percentage of the earth's crust, oceans and atmosphere;

Crust		Oceans		Atmosphere	
Oxygen	47	Oxygen	85	Nitrogen	79
Silicon	27	Hydrogen	10	Oxygen	19
Aluminium	8	Chlorine	2	Argon	2
Iron	5	Sodium	1	Carbon dioxide	0.04
Calcium	4	Magnesium	0.1		
Sodium	3	Sulphur	0.1		
Potassium	3	Calcium	0.04		
Magnesium	2	Potassium	0.04		
Titanium	0.4	Bromine	0.007		
Hydrogen	0.1	Carbon	0.002		
Phosphorus	0.1				
Manganese	0.1				
Fluorine	0.06				
Barium	0.04				
Strontium	0.04				
Sulphur	0.03				
Carbon	0.02				

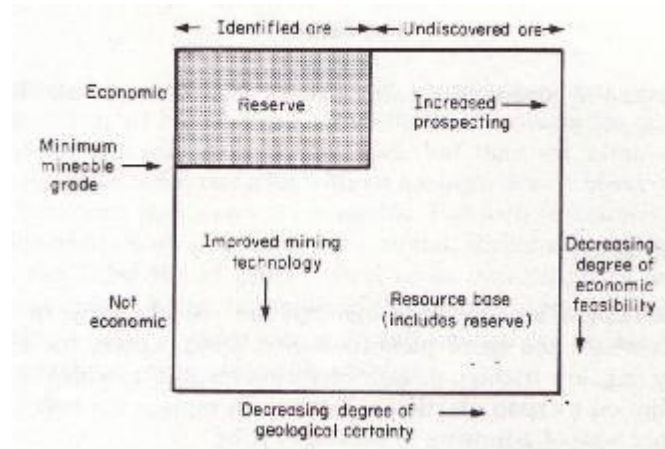
* The total mass of the crust to a depth of 1 km is 3×10^{23} kg; the mass of the oceans is 10^{20} kg; that of the atmosphere is 5×10^{18} kg.

The availability of a resource depends on;

- The degree to which it is localised in one or a few countries (making it susceptible to production controls or cartel action).
- The size of the reserves – the resource base.
- The energy required to mine and process it

In terms of the amount of material it is important to distinguish between the **current reserve** and the **resource base**. The current reserve is the known deposits that can be mined profitably at today's price using today's technology. The resource base however, is the current reserve plus all deposits that might become available given adequate

prospecting and which, by various extrapolation techniques, can be estimated. It also includes all known and unknown deposits that cannot be mined profitably now, but which due to higher prices, better technology or improved transportation, might reasonably become available in the future. Due to the fact that geophysical data and economic projections can be poor, the evaluation of the resource base is subject to vast uncertainty. This relationship between finding resources, and those resources being economical to exploit is summarised in the McElvey diagram;



The choice of materials in the automotive industry

All four groups of materials (steels, polymers, ceramics and composites) play a vital role in the design, construction and service use in vehicle engineering. In addition to the direct engineering issues, the vehicle designer needs to consider the political issues such as pollution and recycling due to the vast quantities of materials used in automotive manufacture. In western Europe, the EC politicians now expect vehicles to be clean, safe, energy efficient and affordable whilst the manufacturers continue to be motivated by profit. Governments are caught between the environmental lobbies and the car industry, which makes a considerable contribution to the gross domestic market.

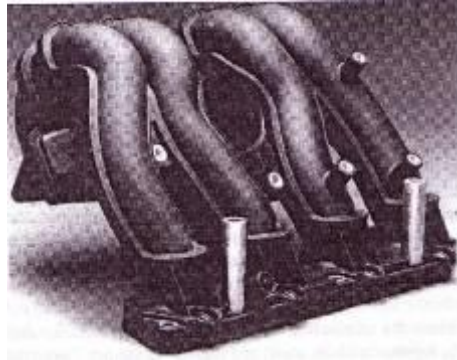
Metals have the wide range of mechanical and physical properties of strength, stiffness and ductility, which are required for most vehicle bodywork and component parts. Consequently, metals and alloys are generally selected by designers for such engineering applications. The current problem with construction steels, in meeting the selection criteria for the automotive industry, is their high density. The total energy costs of owning a car is about 10% to build and 90% to run over its lifetime. Thus, whilst building costs can be reduced, reducing the vehicle weight is easier. Traditionally the car weight would be made up of about 70% steel and 15% cast iron, 4% rubbers and elastomers and the balance being made up of glass, non-ferrous metals, plastics and other polymers.

The weight of plastics and other polymeric materials in cars currently stands at about 250kg. Without plastics the overall weight would increase significantly. Polymeric components are numerous in vehicle construction but can be classified into the following major groups;

- Plastics
 - body parts
 - Interior trim
 - Instrument panels
 - headlamps
- Polymer foams
 - seats
 - Padded safety components for interiors
 - Sound insulation
- Surface coatings, adhesives and sealants
 - Seam finishing
 - Corrosion protection
- Textile fibres
 - Interior trim
 - Carpeting
- Natural and synthetic rubbers
 - Tyres
 - Engine mountings
 - Gaskets
 - Drive belts
 - hoses

These groups do not all carry a load-bearing function but they do help to minimise the almost inevitable weight gains, as manufactures develop new vehicle models with added complexity of safety design, demanded by safety legislation.

A good example of replacing a traditionally metal component with a polymer is the engine manifold shown below. This is a heat resistant nylon with glass fibre reinforcement, which operates up to 130°C and has 35% glass fibre. This replaces a cast aluminium part saving 4-5kg.



Not only is a significant weight save achieved, it is accompanied by better aspiration for the engine which will give better performance. This comes from smoother wall surfaces and lower heat transfer to the incoming air.

Perhaps the most critical parts of the motor vehicle, in terms of loading, temperature, and fatigue, as well as chemical activity, are in the engine and exhaust systems. Ceramic materials are used in this hostile environment ranging from spark plugs to coatings. Ceramics have some excellent engineering properties, such as high strength, good thermal shock resistance, low coefficients of expansion and good thermal and chemical resistance. However, they only have modest fracture toughness and they have high manufacturing costs. The other major use of ceramics in motor vehicles is of course the use glass due to its transparency and social and legislative support. However, significant weight saves (up to 50%) could be achieved by using impact resistant polymer laminates instead.

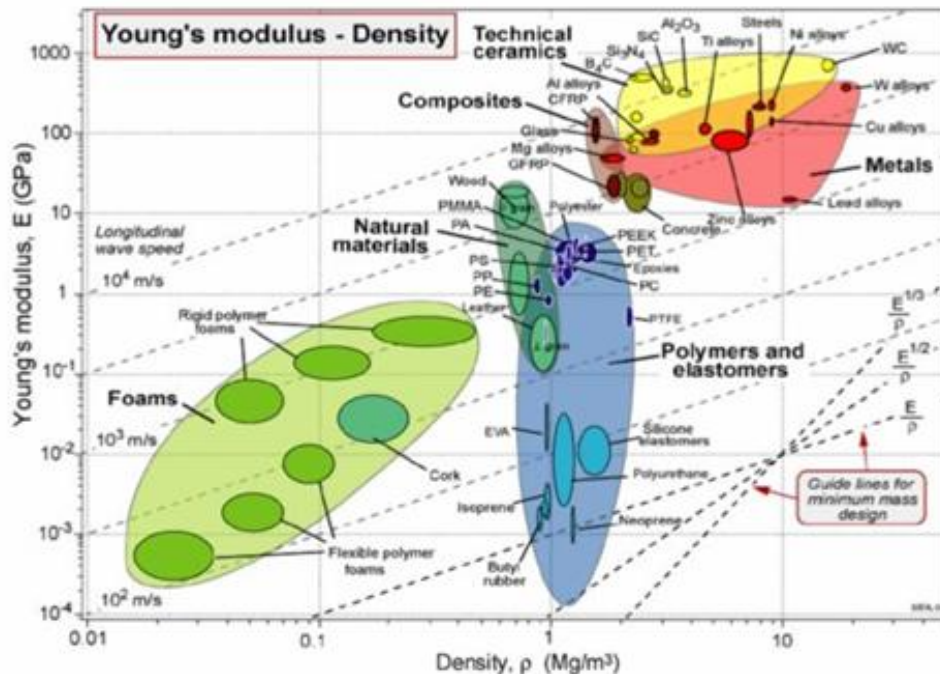
Material Selection Software

In order to help engineers make the correct decisions about which materials and manufacturing processes to use there are several types of Material Selection Software packages available. These packages are basically large databases which provide the engineer with up to date information regarding materials and processes, and allow the engineer to search this information using various criteria.

One example is CES EduPack which is developed by Granta. Granta helps engineering enterprises to apply materials information in order to improve product performance and make better business and design decisions. Their solutions allow engineers to combine the right data (on engineering properties, environmental behavior, and price) with the right specialist tools.

These could be third-party tools - for example, they ensure that accurate, up-to-date, controlled materials data can be accessed within design tools such as computer-aided engineering (CAE) or finite element analysis (FEA) software. Since materials property data is a vital input to the calculations made by such tools, they help to ensure the accuracy of simulations.

A screenshot taken from CES EduPack is shown below which is plotting Young's Modulus against Density for various materials which would be of interest to an engineer looking for a material with a high stiffness/weight ratio.



Notes adapted from/further reading;

Engineering Materials 1 – An introduction to their properties and applications, Michael F Ashby & David R H Jones.
An introduction to Modern Vehicle Design, Julian Hapian-Smith
www.grantadesign.com/