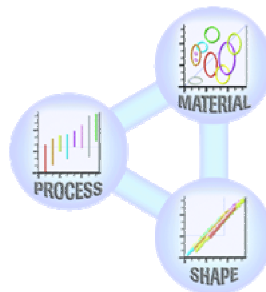
2 - Ashby Method

2.1 - Introduction to Materials Selection

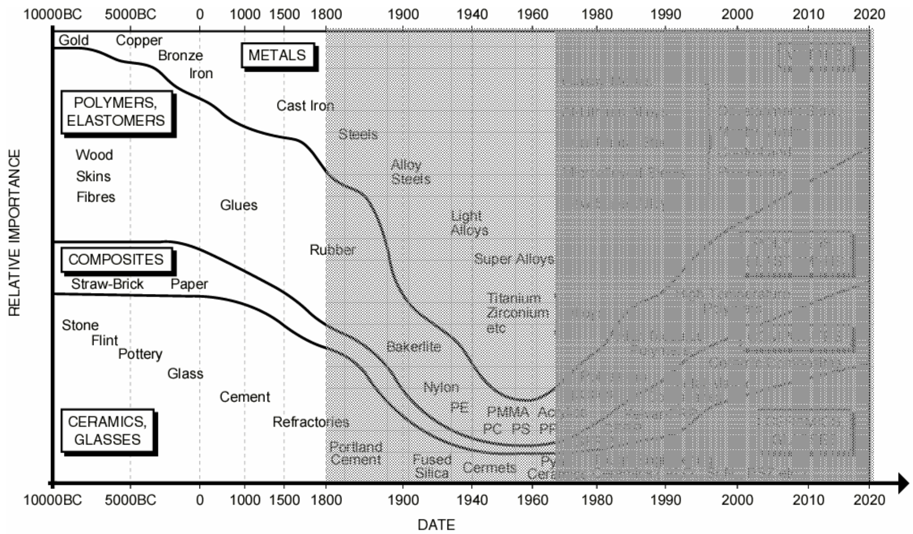


Outline

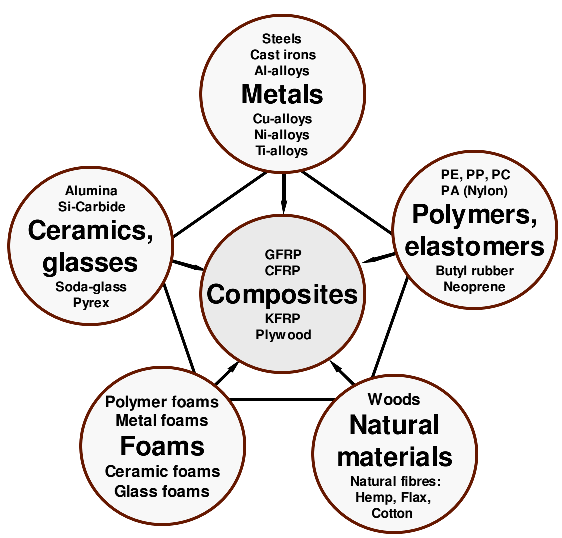
- **Materials and their attributes**
- **Materials and processes data**
- **Exploring relationships: Material Property Charts**
- **Matching material to design: Screening and ranking**
- **Selection strategies and multi-objective optimisation**

Resources:
- M. F. Ashby, "Materials Selection in Mechanical Design" Butterworth Heinemann, 1999
- The Cambridge Material Selector *(CES)* software -- Granta Design, Cambridge (www.grantadesign.com)

The evolution of materials

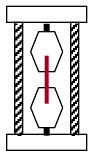


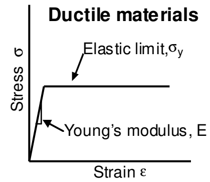
The world of materials

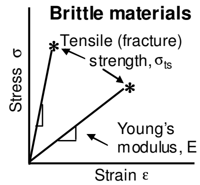


Basic material properties

Mechanical properties







General

Weight: Density ρ, Mg/m^3

Expense: Cost/kg C_m, $/kg

Mechanical

Stiffness: Young's modulus E, GPa

Strength: Elastic limit σ_y, MPa

Fracture strength: Tensile strength σ_{ts}, MPa

Brittleness: Fracture toughness K_{ic}, $MPa.m^{1/2}$

Thermal

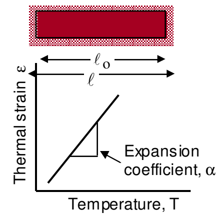
Expansion: Expansion coeff. α, 1/K

Conduction: Thermal conductivity λ, W/m.K

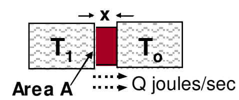
Electrical

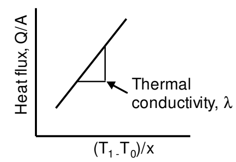
Conductor? Insulator?

Thermal expansion

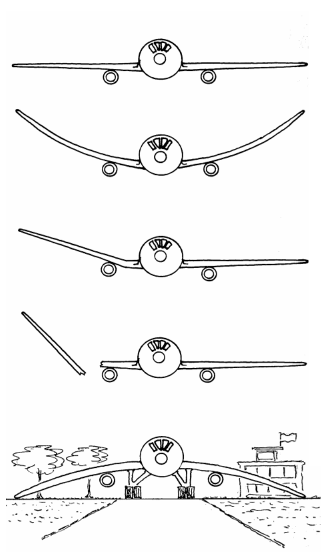


Thermal conduction





Mechanical properties illustrated



Stiff
Strong
Tough
Light
} All OK !

Not stiff enough (need bigger E)

Not strong enough (need bigger σ_y)

Not tough enough (need bigger K_{ic})

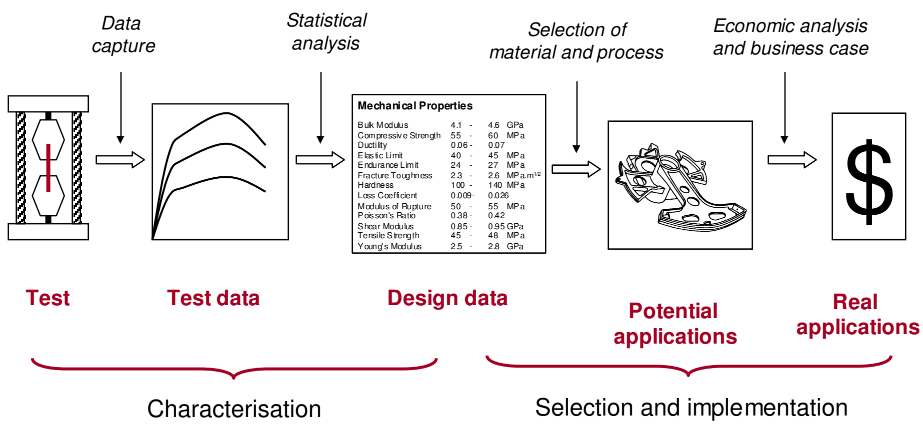
Too heavy (need lower ρ)

Materials information for design

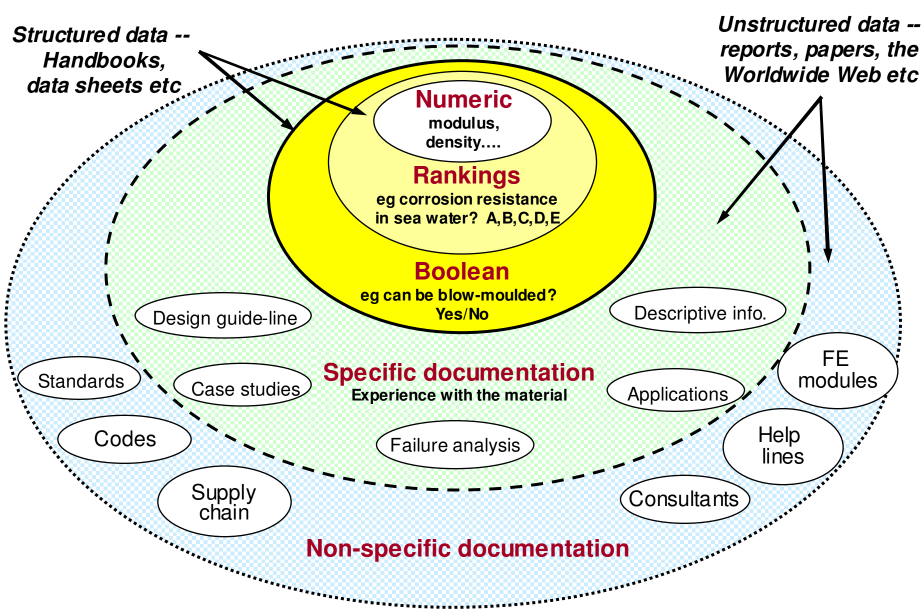
The goals of design:

"To create products that perform their function economically, safely, at acceptable cost"

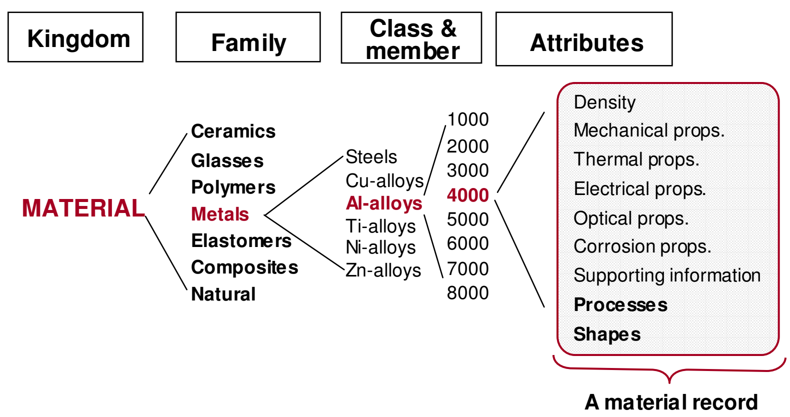
What do we need to know about materials in order to do this?



The nature of material (or process) data



Data organisation: materials



Structured data for ABS

Acrylonitrile-butadiene-styrene (ABS) - $(CH_2\text{-}CH\text{-}C_6H_4)_n$

General Properties

Density	1.05	-	1.07	Mg/m^3
Price	2.1	-	2.3	USD/kg

Mechanical Properties

Bulk Modulus	4.1	-	4.6	GPa
Compressive Strength	55	-	60	MPa
Ductility	0.06	-	0.07	
Elastic Limit	40	-	45	MPa
Endurance Limit	24	-	27	MPa
Fracture Toughness	2.3	-	2.6	$MPa.m^{1/2}$
Hardness	100	-	140	MPa
Loss Coefficient	0.009	-	0.026	
Modulus of Rupture	50	-	55	MPa
Poisson's Ratio	0.38	-	0.42	
Shear Modulus	0.85	-	0.95	GPa
Tensile Strength	45	-	48	MPa
Young's Modulus	2.5	-	2.8	GPa

Thermal Properties

Glass Temperature	350	-	360	K
Max Service Temp	350	-	370	K
Min Service Temp	150	-	200	K
Specific Heat	1500	-	1510	J/kg.K
Thermal Conductivity	0.17	-	0.24	W/m.K
Thermal Expansion	70	-	75	10^{-6}/K

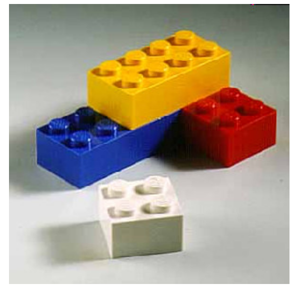
Electrical Properties

Breakdown Potential	14	-	15	MV/m
Dielectric Constant	2.8	-	3.3	
Resistivity	6.3×10^{21}	-	1.6×10^{22}	μ ohm.cm
Power Factor	0.008	-	0.009	

Corrosion and Wear Resistance

Flammability	Average
Fresh Water	Good
Organic Solvents	Average
Oxidation at 500C	Very Poor
Sea Water	Good
Strong Acid	Good
Strong Alkalis	Good
UV	Good
Wear	Poor
Weak Acid	Good
Weak Alkalis	Good

Unstructured data for ABS



What is it? ABS is a terpolymer – one made by copolymerising 3 monomers: acrylonitrile, butadiene and syrene. It is tough, resilient, and easily moulded. ABS is opaque, or at best translucent, but it can be given vivid colours. It is used for casings, telephones, lego bricks, and small moulded parts such as the casings of computer mice. ABS-PVC alloys are tougher than standard ABS and, in self-extinguishing grades, are used for the casings of power tools.

Design Notes. The acrylonitrile gives thermal and chemical resistance, rubber-like butadiene gives ductility and strength, the styrene gives a glossy surface, ease of machining and a lower cost. ABS can be welded to ABS/PC, acrylic and itself, and it can be bonded with polyester, epoxy, alpha-cyanoacylate or nitrile-phenolic adhesives. Ultrasonic welding can reduce the strength of the material to 95% of the original; hot plate welding can reduce the strength to 80%. ABS can be extruded or formed to sheet. Thin (extruded) gauges of ABS can be easily processed on all types of forming equipment. A co-extrusion process or a special film overlay is recommended to extend the life of ABS for outdoor applications. Compression moulded heavy gauge ABS is often used for prototype model making. ABS has the highest impact resistance of all polymers. It allows many colour options and has attractive aesthetic qualities. Integral metallics can be easily added (as in GE Plastics' Magix.) ABS is UV resistant for outdoor application if stabilisers are added.

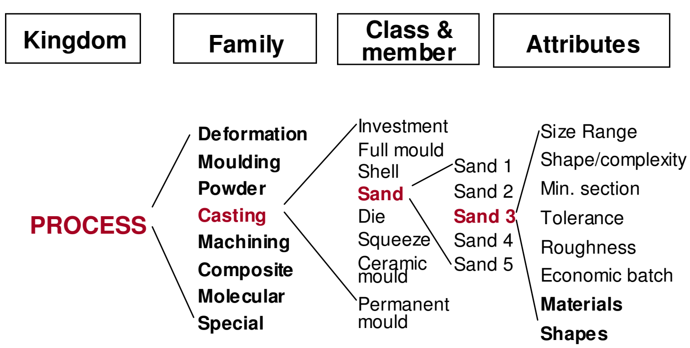
Shaping. ABS is distributed as pellets for moulding or extrusion. The material is normally available a rod or sheet in a range of colours.

Highlights. ABS is FDA compliant. It is readily available, easily machined, bonds well, product versatility, easily formed, good mechanical properties, cost, good impact strength (also at low temperatures), satisfactory stiffness, satisfactory dimensional stability, glossy surface, easy to machine, resistant to some bases and alcohol

Warnings. ABS is hygroscopic (may need to be oven dried before thermoforming), and damaged by petroleum-based machining oils. It has only limited chemical resistance, with poor resistance to solvents.

Typical Uses. Cabinets and cases for domestic goods, TV boxes, telephones, food mixers, vacuum cleaners, baths, showers trays, pipes. Other typical applications include luggage shells, RV parts, business machine housings and parts, shower stalls and cassette holders; automotive parts, housing for tools and appliances, luggage and safety hard hats. Lego, computer mice, razors, handles, shavers, chairs.

Data organisation: processes



Structured data for Green-sand casting

Physical attributes

Size range normal (extreme)	25 - 100 kg
Min. section thickness normal (extreme)	5 - 999 mm
Tolerance, normal (extreme)	1.2 - 3 mm
Surface roughness, normal (extreme)	12 - 25 mm
Aspect ratio	1 - 20
Adjacent section ratio	1 - 5
Hole diameter	30 - 300 mm
Min. corner.radius	5 - 50 mm
Max.dimension	100 - 3000mm
Quality factor (range 1-10)	1 - 4

Economic attributes

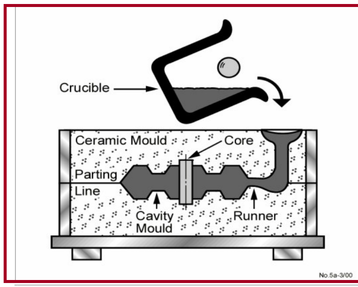
Economic batch size	1 - 1000 units
Capital cost	1000- 5000 £
Tooling cost	100 - 2000 £
Lead time	2 - 4 weeks
Production rate	0.1 - 1 Units/hr
Tool life	10 - 1000 Units
Material utilisation fraction	0.5 - 0.7

Class attributes

Material class	Ferrous, non-ferrous, light alloys
Process class	Discrete, primary shape-forming
Shape class	3-D hollow, transverse features

Unstructured data for Green-sand casting

Name: Sand Casting (green)



Description. In SAND CASTING a mixture of sand and a binder is packed around a pattern that has the shape of the desired casting. The pattern is then removed to leave the cavity in which molten metal is poured. When the metal solidifies, the mould is broken to retrieve the casting.

Design Notes. The pattern is made slightly larger than the desired casting to compensate for shrinkage of the metal as it cools. There are several variations of the process especially in terms of the type of binder used.

Green sand and dry sand moulds refer to sand bonded with clay. Sand casting is not limited to non-refractory, non-reactive metals with melting points below 2000K. Shapers are frequently solid but complex internal shapes can be made using cores

Typical Uses. Very diverse - automotive engineering, machine-tool selectors, Engine blocks, cylinder heads, manifolds, machine-tool frames, pump housing

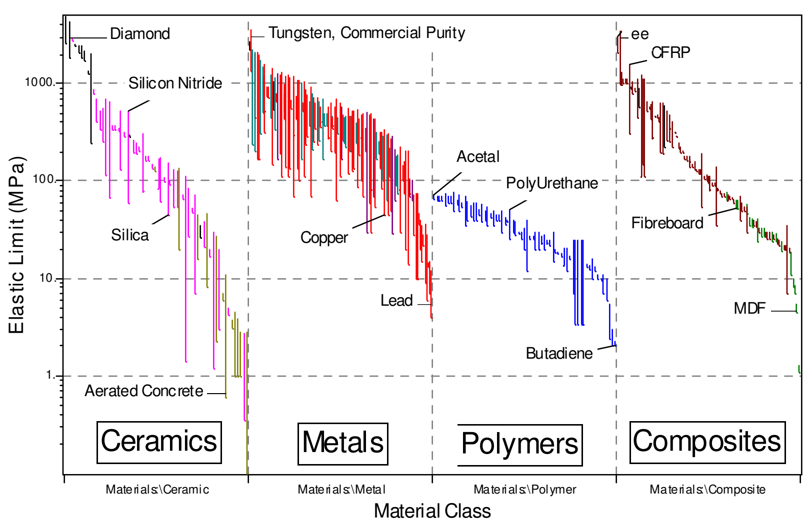
Sources of data.

Bralla, J.G. (1986) “Handbook of Product Design”, McGraw Hill, NY.
Schey, J.A. (1977) “Introduction to Manufacturing Processes”, McGraw Hill, NY.
Clegg, A.J. (1991) “Precision Casting Processes”, Pergamon Press, Oxford U.K.
Metals Hanbook - Vol 15, “Casting”, (1988) 9th Ed. ASM Int Ohio, USA

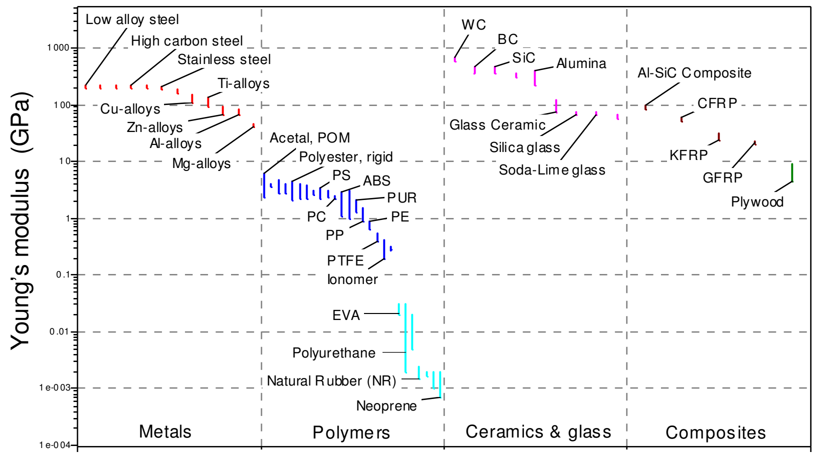
Finding data

- Library searches
- Data Sources compilations such as Chapter 13 of “Materials Selection”
- Locate candidate on CES MATERIALS tree
  or PROCESSES tree and double click
- Use the SEARCH facility to find all records contain candidate name, or trade-name, or application
- Proprietary searchable software: ASM handbooks, B&H Handbooks ……..
- The Worldwide Web, using WEBLINKS to find web sites containing data (e.g. www.matweb.com)

Relationships: property bar-charts



Bar- chart created with *CES*

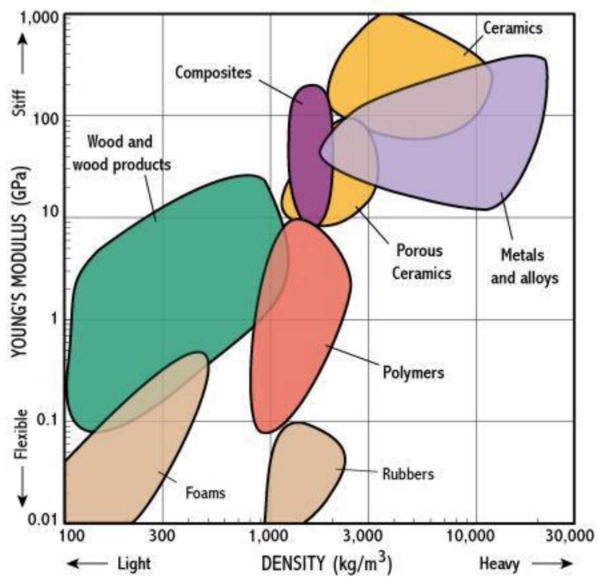


- Explore relationships
- Elementary selection ("Find materials with large elastic limit")

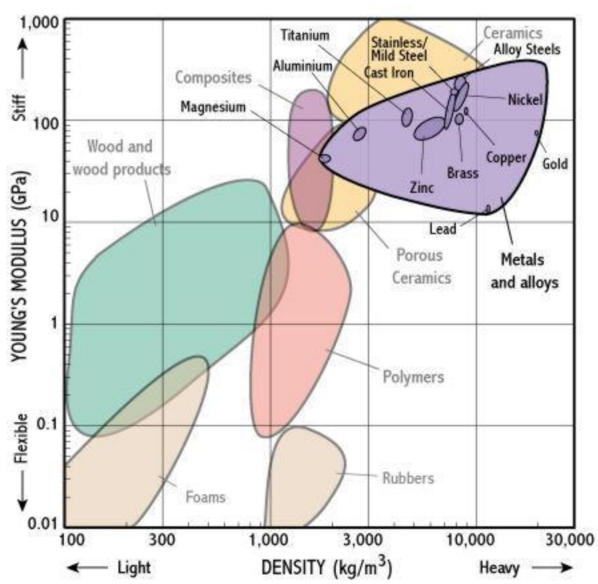
Materials property bubble charts

- Plotting one material property against another.
- Strong focus on strength, modulus, toughness, density, thermal expansion, conductivity, etc.
- Properties usually span 5 decades.
- Properties values cluster according to the six classes of materials.
- Actually eight classes are used because engineering composites are separated from foams and woods and engineering ceramics are separated from porous ceramics.

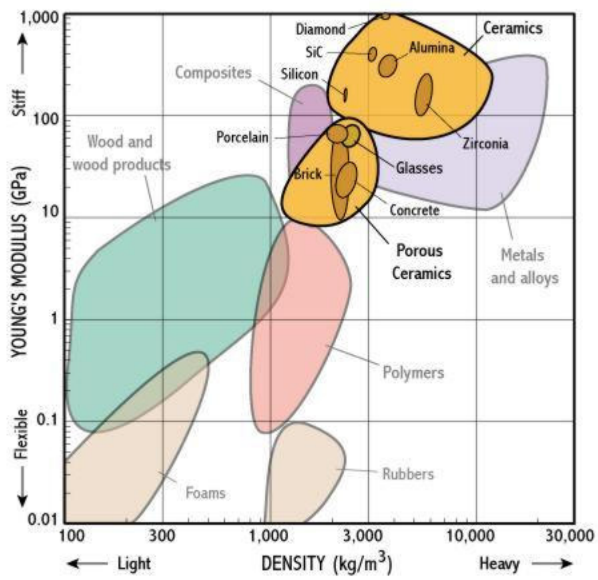
Materials property bubble charts



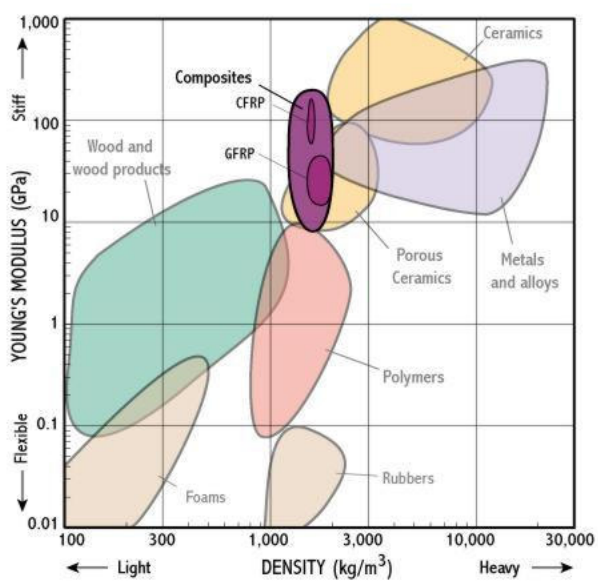
Materials property bubble charts



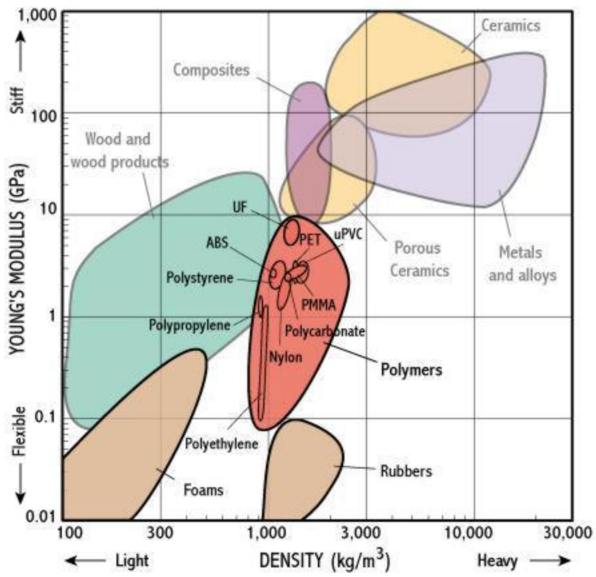
Materials property bubble charts



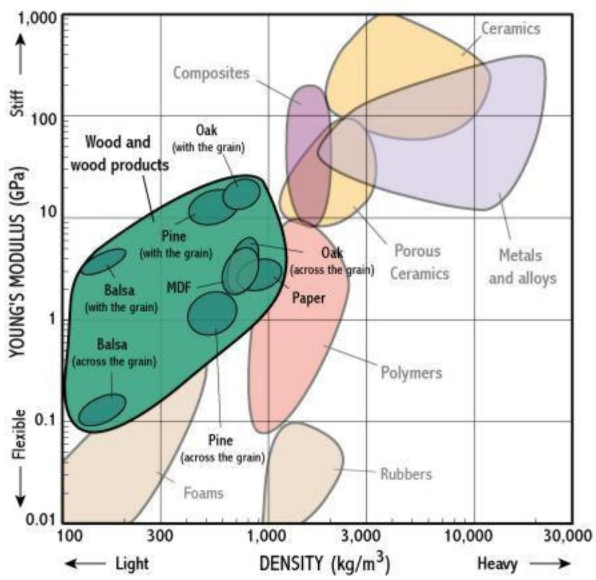
Materials property bubble charts



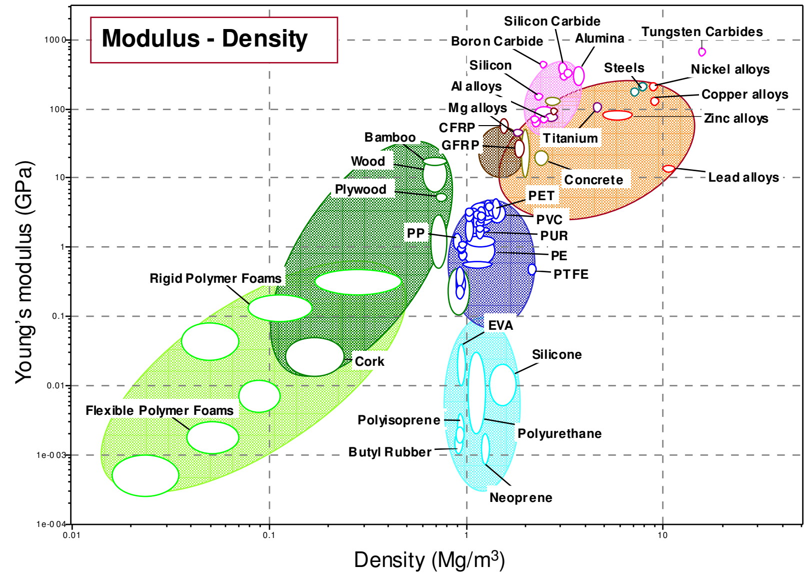
Materials property bubble charts



Materials property bubble charts



Property chart created with *CES*



Materials property bubble charts

- Other parameters that are calculable from the fundamental properties can be represented on these charts as lines of constant value of the parameter.

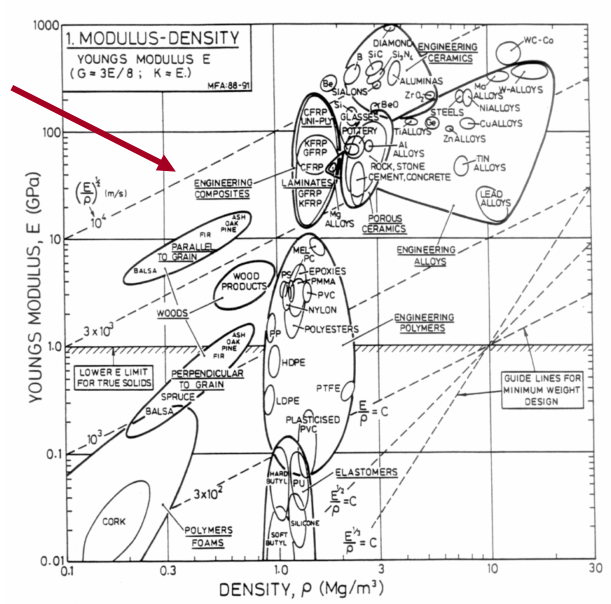
Example: longitudinal wave speed of sound in solid, Modulus vs Density chart.

$$\nu = \left(\frac{E}{\rho}\right)^{1/2}$$

$$\Longrightarrow \quad \mathrm{Log}(E) = \mathrm{Log}(\rho) + 2\mathrm{Log}(\nu)$$

Thus, on a log-log plot iso - ν lines appear as parallel straight lines with a slope of unity.

Materials property bubble charts



The main points

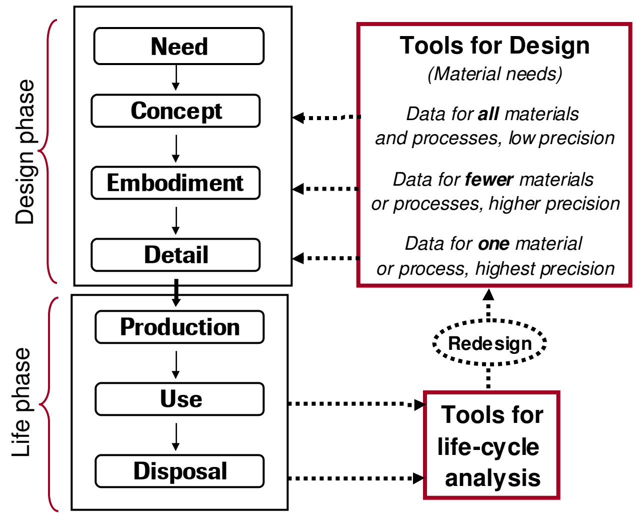
- A classification system for materials allows data for them to be organised
- The data takes several forms:

  (a) numeric, non-numeric data that can be structured in a uniform way for all materials

  (b) supporting information specific to a single material, best stored as text and images
- The organization allows information to be retrieved accurately and efficiently
- Visual presentation of data as bar-charts and property (bubble) charts reveals relationships and allows comparisons

Hard-copies of the charts can be found in Appendix B of the text or downloaded from the Granta web site (www.grantadesign.com)

The design process and data needs



Design requirements ➡ material specification

"Translation"

Design concept

Analyse: Function *What does the component do ?*

Objective(s) *What is to be maximised or minimised ?*

Constraints *What essential conditions must be met ?*

Free variables *Which design variables are free ?*

From which we obtain …

- **Screening criteria** expressed as numerical limits on material property-values

  Or expressed as requirements for processing, corrosion, ….

- **Ranking criteria** based on material indices that characterise performance

Screening by attributes and links

"Eliminate materials that can't do the job"

Screen on attributes — Example: heat exchanger tubes

Requirements: must
- operate at 100^{o}C
- be electrical insulator
- conduct heat well

→

Retain materials with:
- max operating temp > 100C
- resistivity R > 10^{20} $\mu\Omega$.cm
- T-conduct. λ > 100 W/m.K

Screen on links — Example: cheap metal window frame

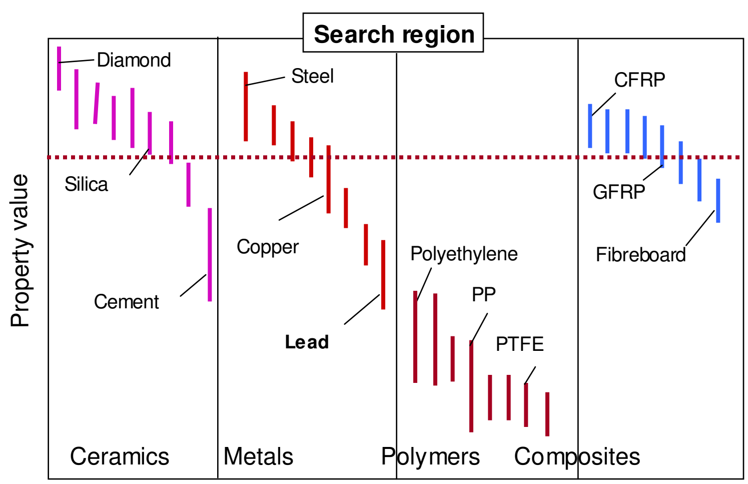
Requirements: must
- be extrudable

→

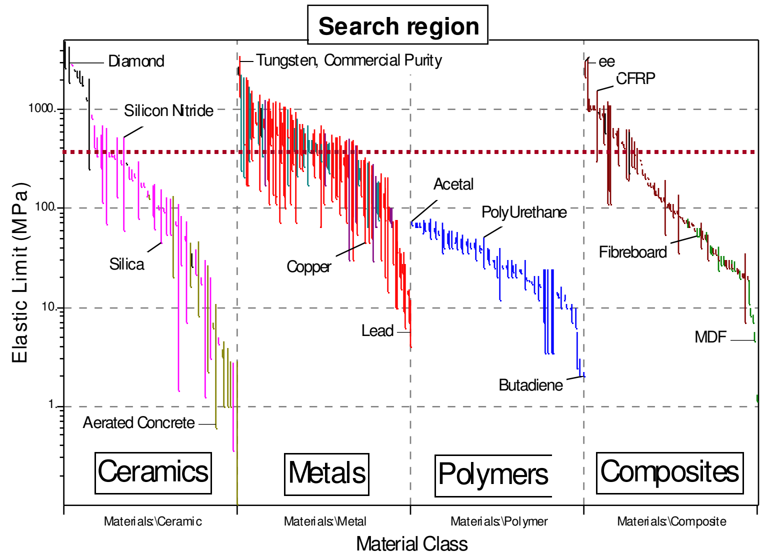
Retain materials with:
- links to "extrusion"

Screen on both attributes and links

Screening using attribute limits



Screening using attribute limits



Ranking by performance

Objective -- a metric of performance, to be maximised or minimised.
Examples: Mass, volume, eco-impact, cost …….per unit of function
Convention: express in form "to be minimised".

Performance metrics: Minimise --

- Cost per unit strength

$$P \propto \frac{C_m}{\sigma_y}$$

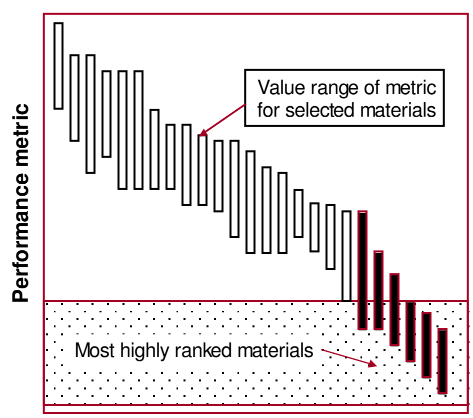
- Mass per unit bending stiffness

$$P \propto \frac{\rho}{E^{1/2}}$$

- Volume per unit energy absorbed

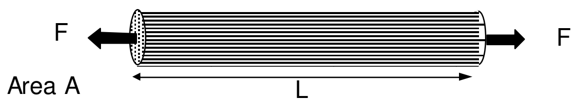
$$P \propto \frac{1}{\sigma_y \varepsilon_D}$$

- Many more ………………



Material indices

Strong tie of length L and minimum mass



Function *Tie-rod*

Constraints *Length L is specified*
Must not fail under load F

Objective *Minimise mass m*

Free variable *Cross-section area A is free*

Equation for objective: $m = A L \rho$ (1)

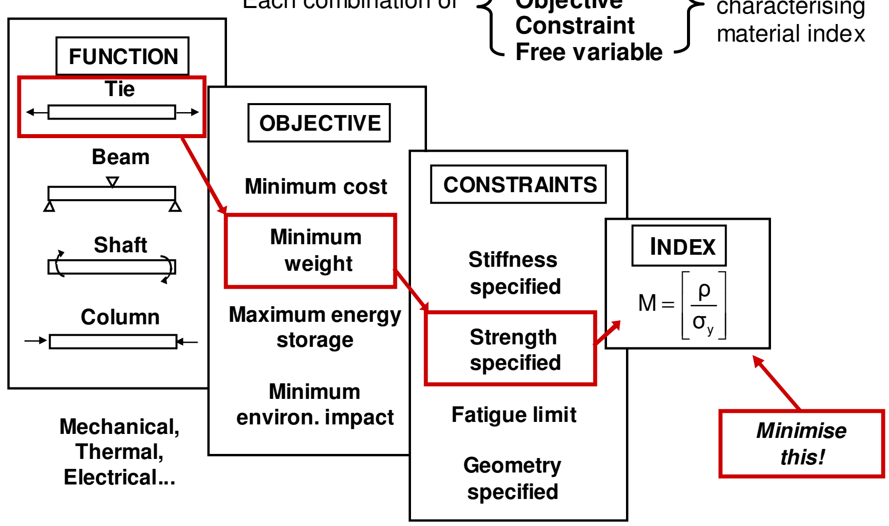
Equation for constraint: $F/A < \sigma_y$ (2)

Eliminate A in (1) using (2): $m = FL\left(\frac{\rho}{\sigma_y}\right)$

Minimise the material index $\left(\frac{\rho}{\sigma_y}\right)$

Materials indices

Each combination of **Function**, **Objective**, **Constraint**, **Free variable** — Has a characterising material index



Material indices: the key to optimised choice

Material properties --

the "Physicists" view of materials, e.g.

Cost,	C_m
Density,	ρ
Modulus,	E
Strength,	σ_y
Endurance limit,	σ_e
Thermal conductivity,	λ
T- expansion coefficient,	α

Material indices --

the "Engineers" view of materials

Objective: minimise mass

Function	Stiffness	Strength
Tension (tie)	ρ/E	ρ/σ_y
Bending (beam)	$\rho/E^{1/2}$	$\rho/\sigma_y^{2/3}$
Bending (panel)	$\rho/E^{1/3}$	$\rho/\sigma_y^{1/2}$

Minimise these!

Many more: see Appendix B of the Text

Selection using charts

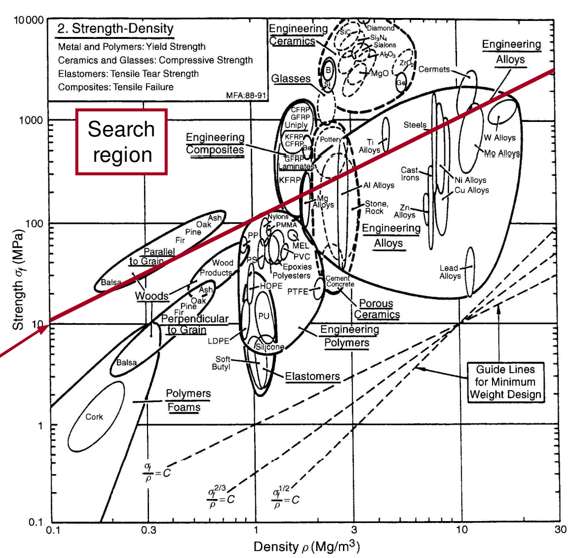
$$C = \frac{\rho}{\sigma_y}$$

$$\Rightarrow \sigma_y = \rho / C$$

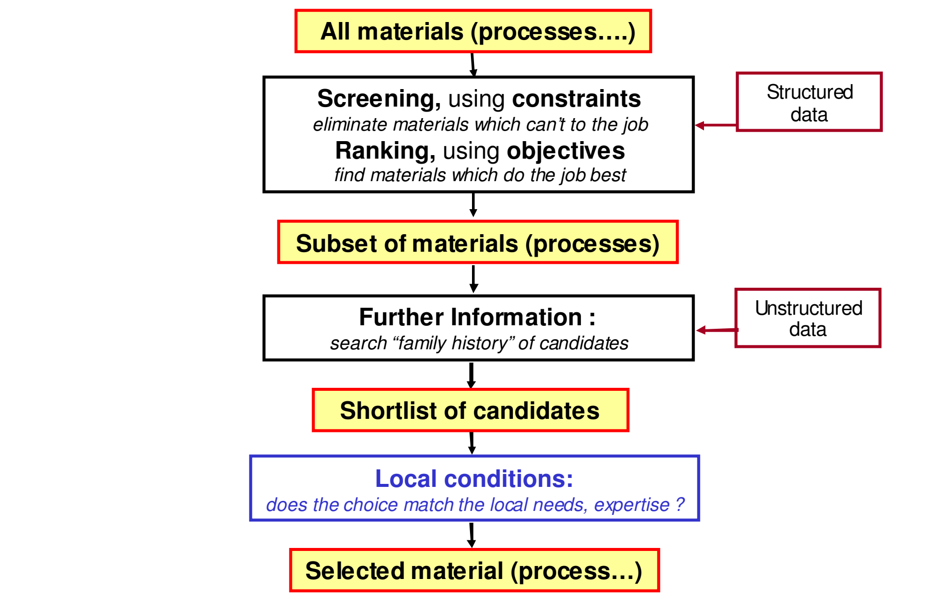
$$\text{Log}(\sigma_y) = \text{Log}(\rho) - \text{Log}(C)$$

$$\frac{\rho}{\sigma_y} = C$$

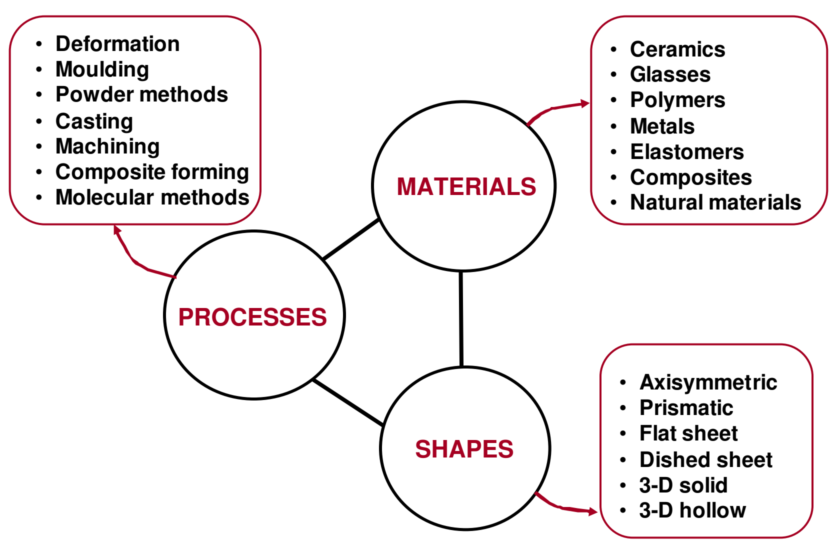
Contours of constant C are lines of slope 1 on an σ_y-ρ chart



Steps of selection



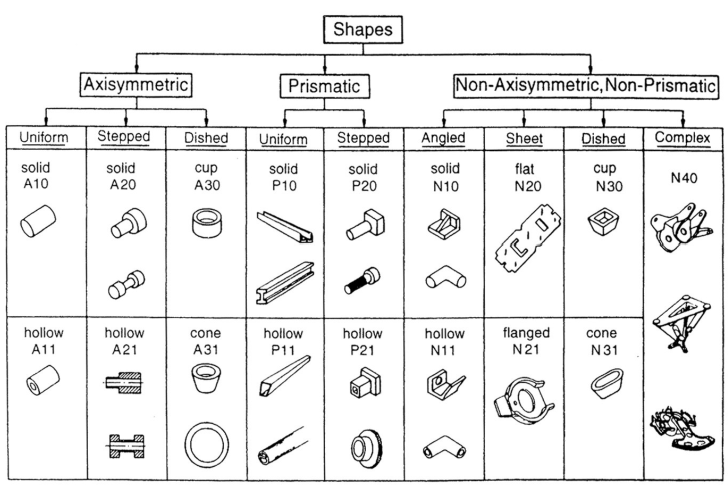
Materials, processes and shapes



Materials, processes and shapes

Process Class		Metals					Ceramics & Glasses				Polymers & Elastomers			Composites		
		Ferrous	Refractory	Precious	Heavy	Light	Cementitous	Vitreous	Fine	Glasses	Thermosets	Thermoplastics	Elastomers	PMCs	MMCs	CMCs
Casting	Gravity	2	1	2	2	2	0	0	0	1	0	0	0	0	0	0
	Low pressure	2	0	2	2	2	0	0	0	2	0	0	0	0	1	0
	High pressure	1	0	2	2	2	0	0	0	1	0	0	0	0	2	0
	Investment	2	2	2	2	2	0	0	0	0	0	0	0	0	0	0
Moulding	Injection	0	0	2	0	0	0	0	0	2	2	2	2	2	0	0
	Compress	0	0	2	0	0	0	0	0	2	2	2	2	2	1	0
	Blow	0	0	0	0	0	0	0	0	2	0	2	0	0	0	0
	Foam	0	0	0	0	0	0	0	0	0	2	2	2	0	0	0
Deformation	Cold	2	0	2	2	2	0	0	0	0	0	0	0	0	0	0
	Warm	2	0	2	2	2	0	0	0	0	0	0	0	0	0	0
	Hot	2	2	2	2	2	0	0	0	2	0	0	0	0	0	0
	Sheet	2	1	2	2	2	0	0	0	0	0	2	0	0	1	0
Machining	Turn	2	2	2	2	2	0	1	0	0	2	2	0	2	2	0
	Mill	2	2	2	2	2	0	1	0	0	2	2	0	2	2	0
	Grind	2	2	1	2	2	0	2	2	2	0	0	0	0	2	2
	Polish	2	2	2	2	2	0	2	2	2	0	0	0	0	1	2
Powder Methods	Sinter/HIP	2	2	2	2	2	0	2	2	1	0	2	0	0	2	2
	Slip cast	0	0	0	0	0	0	2	2	1	0	0	0	0	0	1
	Spray forming	2	2	2	2	2	0	2	2	2	2	2	0	2	0	0
	Hydration	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
Composite Forming	Lay-up	0	0	0	0	0	0	0	0	0	0	0	0	2	0	2
	Mould	0	0	0	0	0	0	0	0	0	2	2	2	2	0	0
	Squeeze-cast	1	0	0	2	2	0	0	0	0	0	0	0	0	2	0
	Filament wind	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0
Molecular Methods	PVD	0	2	2	2	0	0	0	2	.0	0	0	0	0	1	0
	CVD	0	2	2	2	0	0	0	2	0	0	0	0	0	1	2
	Sputtering	2	2	2	2	2	0	0	0	0	0	0	0	0	0	0
	Electroforming	1	0	2	2	0	0	0	0	0	0	0	0	0	0	0
Special Methods	Electrochemical	2	2	2	2	2	0	0	0	0	0	0	0	0	2	0
	Ultrasonic	1	2	0	0	0	0	2	2	2	0	0	0	0	0	2
	Chemical	2	2	2	2	2	0	2	2	2	0	0	0	0	0	0
	Thermal Beam	2	2	2	2	2	0	2	2	2	2	2	2	2	2	2
Fabrication	Weld/braze	2	2	2	2	2	0	0	0	0	0	2	0	0	0	0
	Adhesive	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	Fasten	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	Microfabrication	2	2	2	2	2	0	2	2	2	2	2	2	2	2	2

Materials, processes and shapes



Materials, processes and shapes

Process Class		Shapes: Axisymmetric						Prismatic				Non-Axisymmetric, Non-Prismatic						
		A10	A11	A20	A21	A30	A31	P10	P11	P20	P21	N10	N11	N20	N21	N30	N31	N40
Casting	Gravity	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Low pressure	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1
	High pressure	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1
	Investment	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Moulding	Injection	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1
	Compress	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1
	Blow	0	1	0	1	1	1	0	0	0	0	0	0	0	0	1	1	0
	Foam	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	0
Deformation	Cold	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1
	Warm	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1
	Hot	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1
	Sheet	0	1	0	1	1	1	0	1	0	1	1	1	1	1	1	1	0
Machining	Turn	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	1
	Mill	0	0	0	0	0	0	1	0	1	1	1	0	1	1	1	1	1
	Grind	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Polish	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Powder Methods	Sinter/HIP	1	1	1	1	0	0	1	1	1	1	0	0	1	1	0	0	0
	Slip cast	0	0	0	0	1	1	0	0	0	0	0	0	0	0	1	1	0
	Spray forming	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
	Hydration	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Composite Forming	Lay-up	0	1	0	1	1	1	1	1	1	1	1	0	1	1	0	0	1
	Mould	0	1	0	1	1	1	0	0	0	0	0	1	1	1	1	1	1
	Squeeze-cast	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1
	Filament wind	0	1	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0
Molecular Methods	PVD	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
	CVD	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Sputtering	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Electroforming	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Special Methods	Electrochemical	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Ultrasonic	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Chemical	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Thermal beaming	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Fabrication	Weld/braze	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Adhesive	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Fasten	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Microfabrication	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

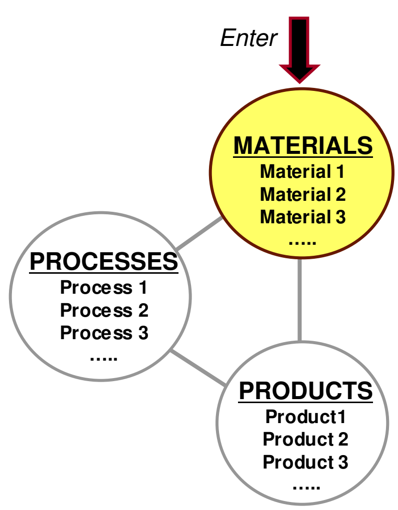
Selection by technical analysis

Select on material properties alone

Find material that has

- Attribute 1 < C_1 **(Density, ρ)**
- Attribute 2 > C_2 **(Modulus, E)**
- Attribute 3 > C_3 **(Strength, σ)**
- Attribute 4 = C_4 **(Poisson, ν)**

Multiple constraints



Selection by association

Select on processability and material properties

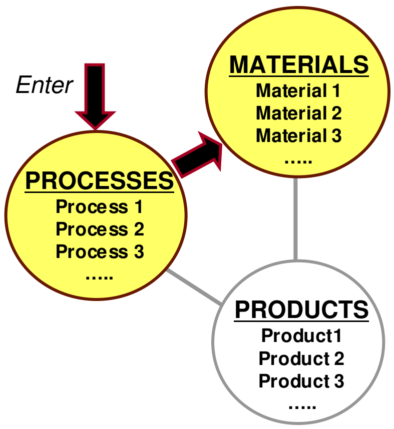
Find material that of type

"INJECTION MOULDABLE"

and has

- Attribute 1 > C_1
- Attribute 2 > C_2
- Attribute 3 < C_3
- Attribute 4 < C_4

Multiple constraints



Selection by analogy

Select on similarity (and innovative substitution)

Find material that is like Material X, or like that of Product Z

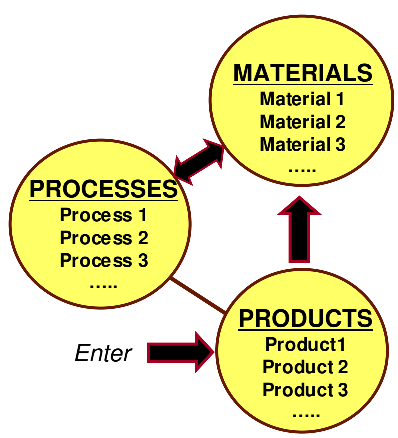
but has

- Attribute 1 > C_1
- Attribute 4 < C_4

Additional constraints

and is of type

"SAND-CASTABLE"

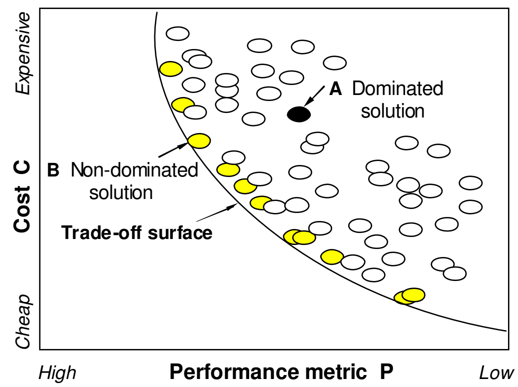


Multi-objective optimisation for selection

- **How balance objectives ? eg**

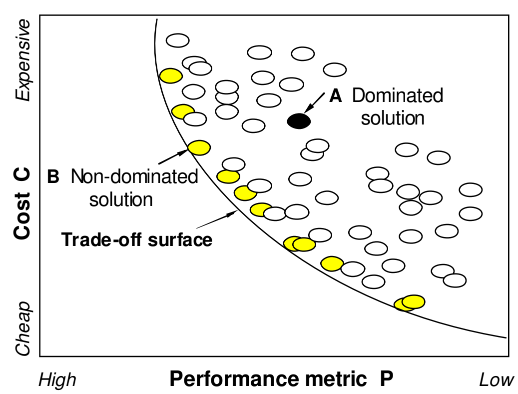
Performance, P } Conflicting
Cost, C } objectives

- **Plot performance metric P against cost metric C**
- **A "solution",** is a material with a given combination of cost and performance
- **Dominated** and **non-dominated** solutions



Multi-objective optimisation for selection

- ***Solution:*** a viable choice, meeting constraints, but not necessarily optimum by either criterion.
- ***Dominated solution (A):*** some other solution is better by both metrics
- ***Non-dominated solution (B):*** no one other solution is better by both metrics



- The **trade-off surface** (or Pareto front) is the surface on which the non-dominated solutions lie
- Use **intuition** to select
- Form a **value function**: a composite objective

Multi-objective optimisation for selection