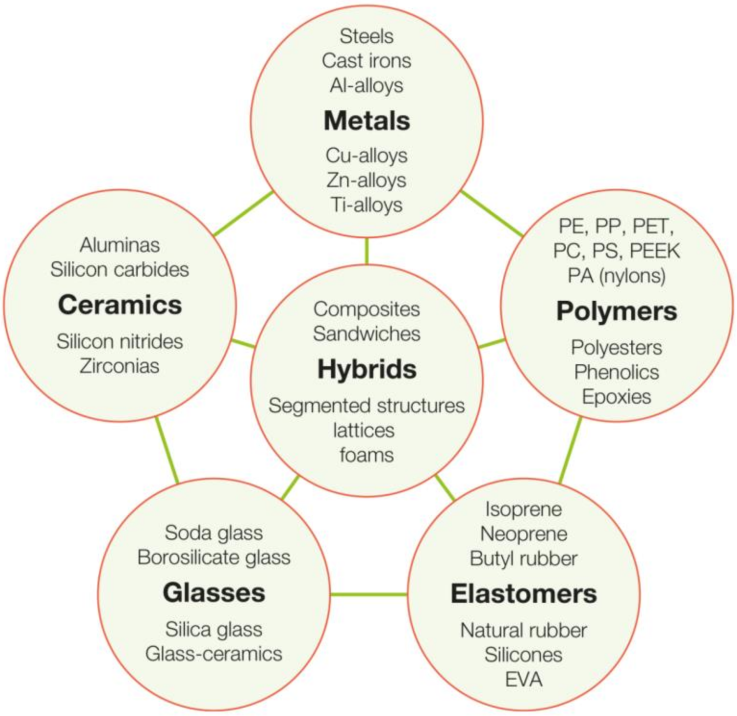
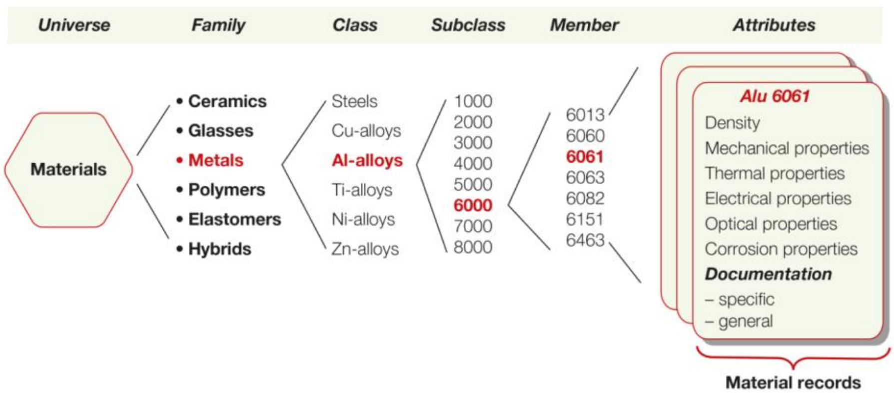
Material Selection – Massow

Families:





Example

Metals – Steel -1.4301

Material Properties

Classes:

- General
- Mechanical
- Thermal
- Electrical

- Optical
- Eco-properties

Class	Property	Symbol and Units
General	Density	ρ (kg/m^3 or Mg/m^3)
	Price	C_m (\$/kg)
Mechanical	Elastic moduli (Young's, shear, bulk)	E, G, K (GPa)
	Yield strength	σ_y (MPa)
	Tensile (ultimate) strength	σ_{ts} (MPa)
	Compressive strength	σ_c (MPa)
	Failure strength	σ_f (MPa)
	Hardness	H *(Vickers)*
	Elongation	ε (–)
	Fatigue endurance limit	σ_e (MPa)
	Fracture toughness	K_{1c} (MPa.m$^{1/2}$)
	Toughness	G_{1c} (kJ/m^2)
	Loss coefficient (damping capacity)	η (–)
	Wear rate (Archard) constant	K_AMPa^{-1}
Thermal	Melting point	T_m (°C or K)
	Glass temperature	T_g (°C or K)
	Maximum service temperature	T_{max} (°C or K)
	Minimum service temperature	T_{min} (°C or K)
	Thermal conductivity	λ (W/m.K)
	Specific heat	C_p (J/kg.K)
	Thermal expansion coefficient	α (K^{-1})
	Thermal shock resistance	ΔT_s (°C or K)
Electrical	Electrical resistivity	ρ_e (Ω.m or $\mu\Omega$.cm)
	Dielectric constant	ε_r (–)
	Breakdown potential	V_b (10^6 V/m)
	Power factor	P (–)
Optical	Refractive index	n (–)
Eco-properties	Embodied energy	H_m (MJ/kg)
	Carbon footprint	CO_2 (kg/kg)

Choice of Material

- Dictated by the design & vice versa
- Not independent of the choice of process
- Influences costs
- Influences sustainability & ecological footprint
- Important for industrial design
    - Form, texture, haptic, colour
    - "good design works; excellent design also gives pleasure"

IMPORTANT to examine the full range of materials & not to reject option because they are unfamiliar

Over 120 000 materials available

Material Selection Strategy

- Translation
    - Define requirements
    - Constraint equations
    - Objective equation
    - Identify free variables
    - Substitute free variables

- Group variables
- Material index

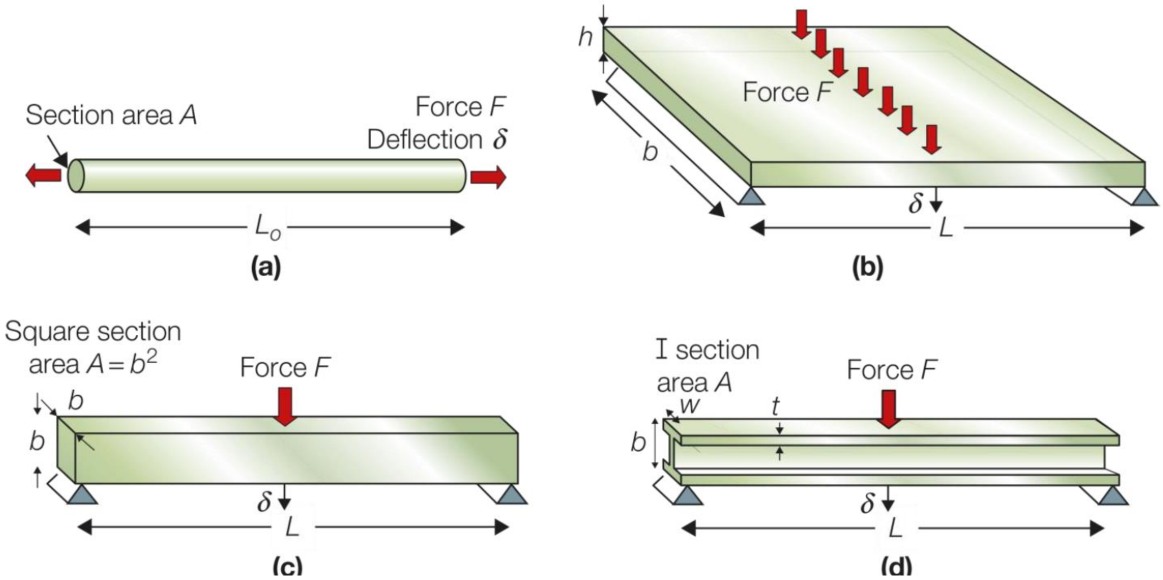
- Screening
- Ranking
- Documentation

Functional names of components

a) Ties – carry tensile loads
b) Plates – load on area
c) Beams – carry bending load
d) Beams – carry bending load

Shafts – carry torque

Columns – carry compressive axial loads



Multiple Constraints

<u>Analytical Method</u>

Selection of a material for a light, stiff, strong tie

$$L^* = 1\,\text{m} \quad S^* = 3 \times 10^7\ \text{N/m} \quad F_f^* = 10^5\,\text{N}$$

Material	ρ **Kg/m^3**	***E* GPa**	σ_y **MPa**	m_1 **kg**	m_2 **kg**	$\tilde{m}$ **kg**
1020 Steel	7,850	200	320	1.12	2.45	2.45
6061 Al	2,700	70	120	1.16	2.25	2.25
Ti-6-4	4,400	115	950	1.15	0.46	1.15

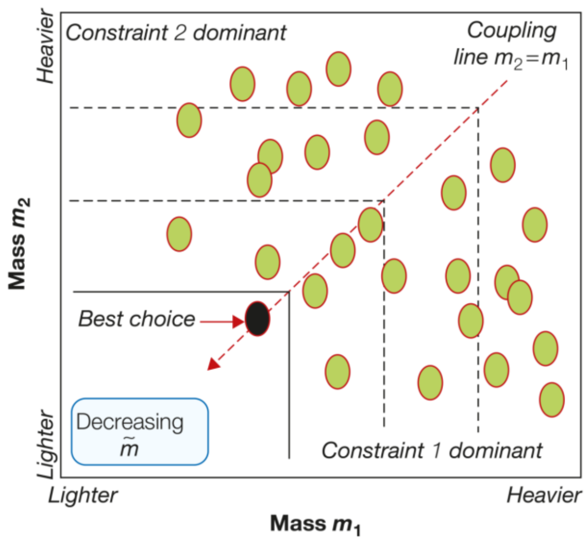
If the constraints are changed to

$$L^* = 3\ \text{m} \qquad S^* = 10^8\text{N/m} \qquad F_f^* = 3 \times 10^4\,\text{N}$$

the selection changes. Now steel is the best choice: It gives the lightest tie that satisfies all the constraints

<u>Graphical Method</u>

- Plot m_2 against m_1 for each member of a population of materials
- Coupling line $m_2 = m_1$ separates two regions; constraint 1 dominant ($m_1 > m_2$); constraint 2 dominant ($m_2 > m_1$);
- The material with the smallest possible mass is the one left when pulling a box-shaped selection envelope to the bottom left
- If the constraints are changed, the chart changes & selection has to be repeated



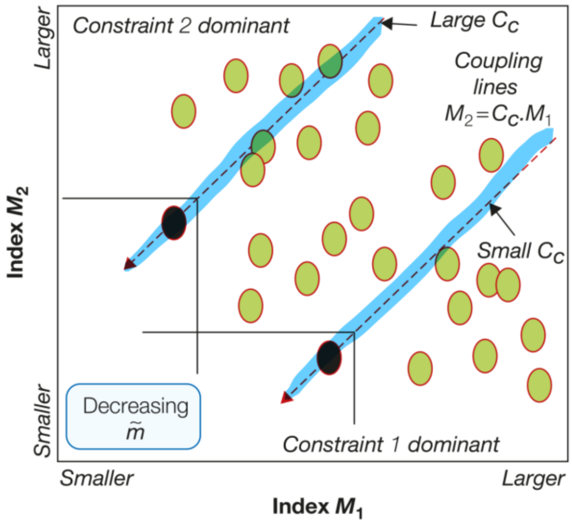
- Plot material indices M_2 against M_1 for each member of a population of materials

- Coupling line is found to be

$$m_1 = m_2$$
$$\Leftrightarrow L^{*2} S^* M_1 = L^* F_f^* M_2 \qquad | C_c = \frac{L^* S^*}{F_f^*}$$
$$\Leftrightarrow M_2 = C_c M_1$$
$$\Leftrightarrow \log(M_2) = \log(M_1) + \log(C_c)$$

where C_c is the coupling constant

- If the constraints are changed, the coupling line is shifted in parallel

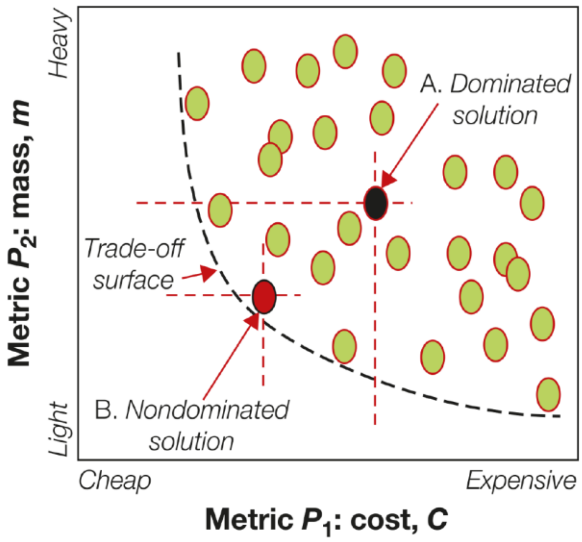


Conflicting Objectives

<u>Trade-off Strategies</u>

Objectives are characterized by performance metrics P_i; e.g. minimize cost P_1 and minimize mass P_2

- Plot P_1 against P_2 for alternative solutions
  - Dominated solutions:
    solutions having lower values of both P_1 and P_2 exist
  - Nondominated solutions:
    solutions having lower values of both P_1 and P_2 do not exist
  - Trade-off surface:
    links nondominated solutions



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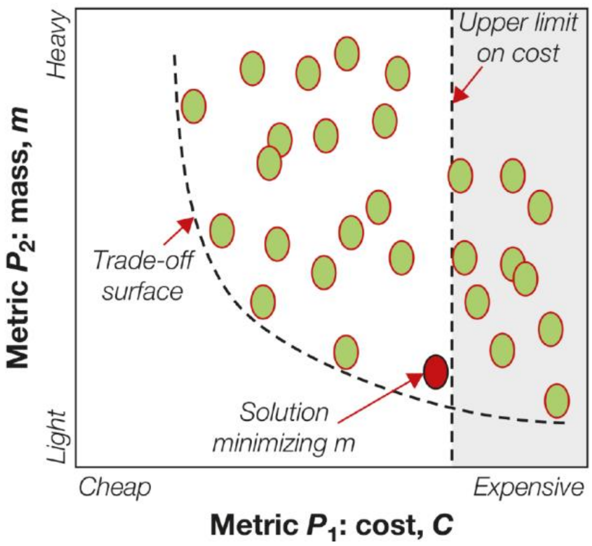
- Three strategies for further progressing
  - Strategy 1
    Identify a shortlist using intuition
  - Strategy 2
    Reformulate one objective as a constraint by setting an upper limit
  - Stategy 3
    Use penalty functions



Penalty functions

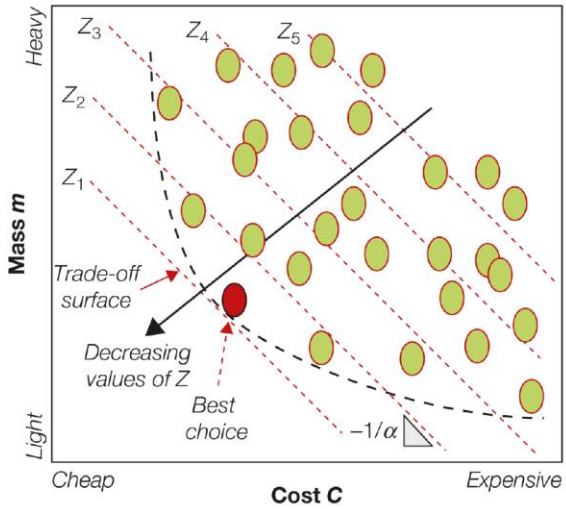
Frequently one of the performance metrics is cost C; advantageous to measure Z in units of currency

$$Z = \alpha_1 P_1 + \alpha_2 P_2 + \alpha_3 P_3 + ... \quad | \quad P_1 = C$$
$$\Rightarrow \alpha_1 = 1$$
$$\Leftrightarrow Z = C + \alpha_2 P_2 + \alpha_3 P_3 + ...$$

e.g. P_1 = cost C; P_2 = mass m

$$Z = C + \alpha m$$
$$\Leftrightarrow m = -\frac{1}{\alpha} C + \frac{1}{\alpha} Z$$

leads to family of parallel penalty lines; line tangential to trade-off surface shows optimum solution



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e.g. P_1 = cost C; P_2 = mass m

$$Z = C + \alpha m$$
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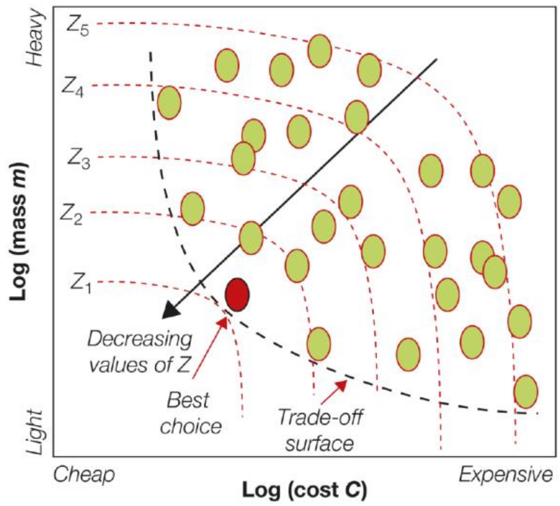
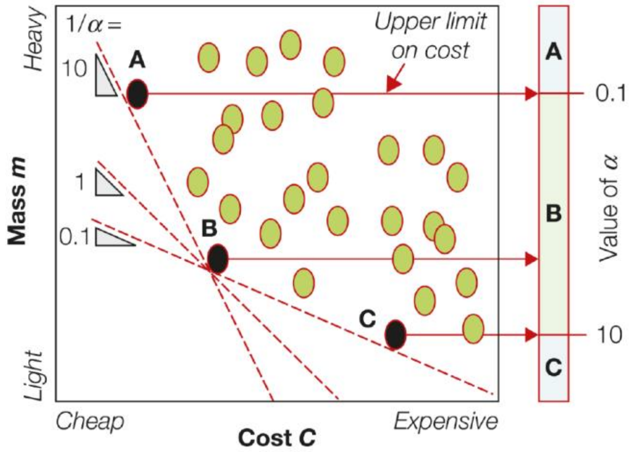
leads to family of curved penalty lines on logarithmic scales; line touching trade-off surface shows optimum solution



Exchange constants

- Useful engineering decisions can be reached even when exchange constants are imprecisely known
  - A given solution on the trade-off surface is optimal for a certain range of values of α
  - Range can be large, so any value of α within the range leads to the same choice of material



Material and Shape

Shape can be used to increase the mechanical efficiency of a material

Shape – refers to form of the components

Mechanical efficiency – refers to the use of as little material as possible

Best material-shape combination depends on the mode of loading!

<u>Shape Factor</u>

Characterizing the efficiency of material use in load cases

- ϕ^e_B for elastic bending of beams
- ϕ^e_T for elastic twisting of shafts
- ϕ^f_B for plastic failure at bending of beams
- ϕ^f_T for plastic failure at twisting of shafts

Bending stiffness of beams

$$S = \frac{F}{\delta} \qquad \phi_B^e = \frac{S}{S_0}$$

$$S = \frac{C_1 EI}{L^3} \qquad \phi_B^e = \frac{12I}{A^2}$$

Elastic twisting of stafts

$$S_T = \frac{T}{\varphi} \qquad \phi_T^e = \frac{S_T}{S_{T0}}$$

$$S_T = \frac{KG}{L} \qquad \phi_T^e = 7.14\frac{K}{A^2}$$

Plastic failure at bending of beams

$$\phi_B^f = \frac{M_f}{M_{f0}}$$

$$\phi_B^f = 6\frac{Z}{A^{\frac{3}{2}}} \qquad \sigma = \frac{M}{Z}$$

Plastic failure at twisting of shafts

$$\phi_T^f = \frac{T_f}{T_{f0}}$$

$$\phi_T^f = 4.8\frac{Q}{A^{\frac{3}{2}}} \qquad \tau = \frac{T}{Q}$$

NEW ORDER

i)Define design requirements

ii)Derive equations for the constraints (where necessary): the constraint equations

iii)Replace factors in the constraint equations that are influenced by the shape with the corresponding shape factors

iv)Derive an equation for the objective: the objective function

v)Identify the free (unspecified) variables

vi)Substitute the free variables from the constraint equations (including shape factors) into the objective function

vii)Group the variables of the performance metric (P) into three groups: functional requirement (F), geometric parameters (G), and material properties & shape factors (M, ϕ); thus

P ≥ f1(F)·f2(G)·f3(M, ϕ) or

P ≤ f1(F)·f2(G)·f3(M, ϕ)

viii)Read off the material index including the shape factor that optimizes the performance metric