KU LEUVEN

An introduction to the possibilities of Materials Selection.

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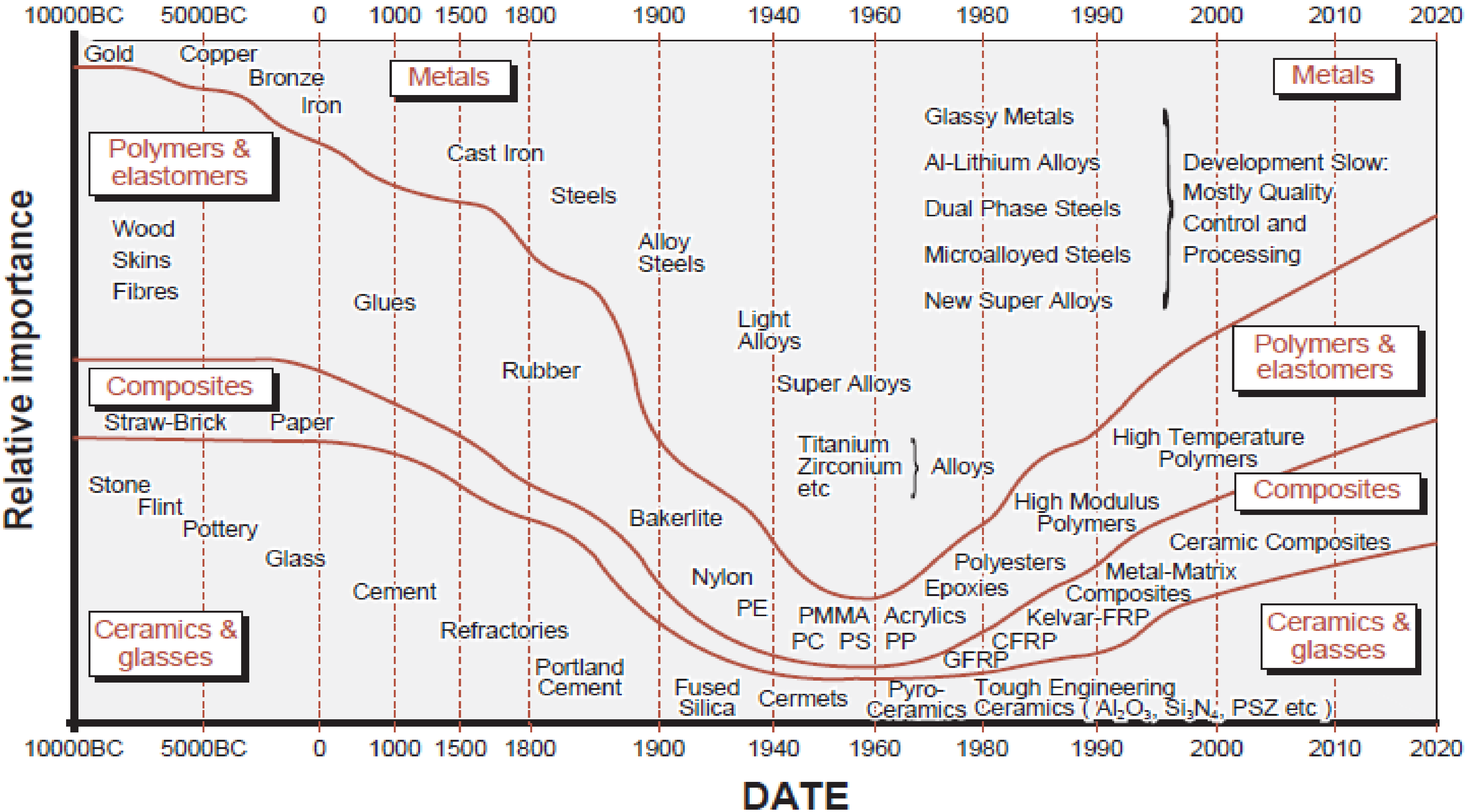
Content

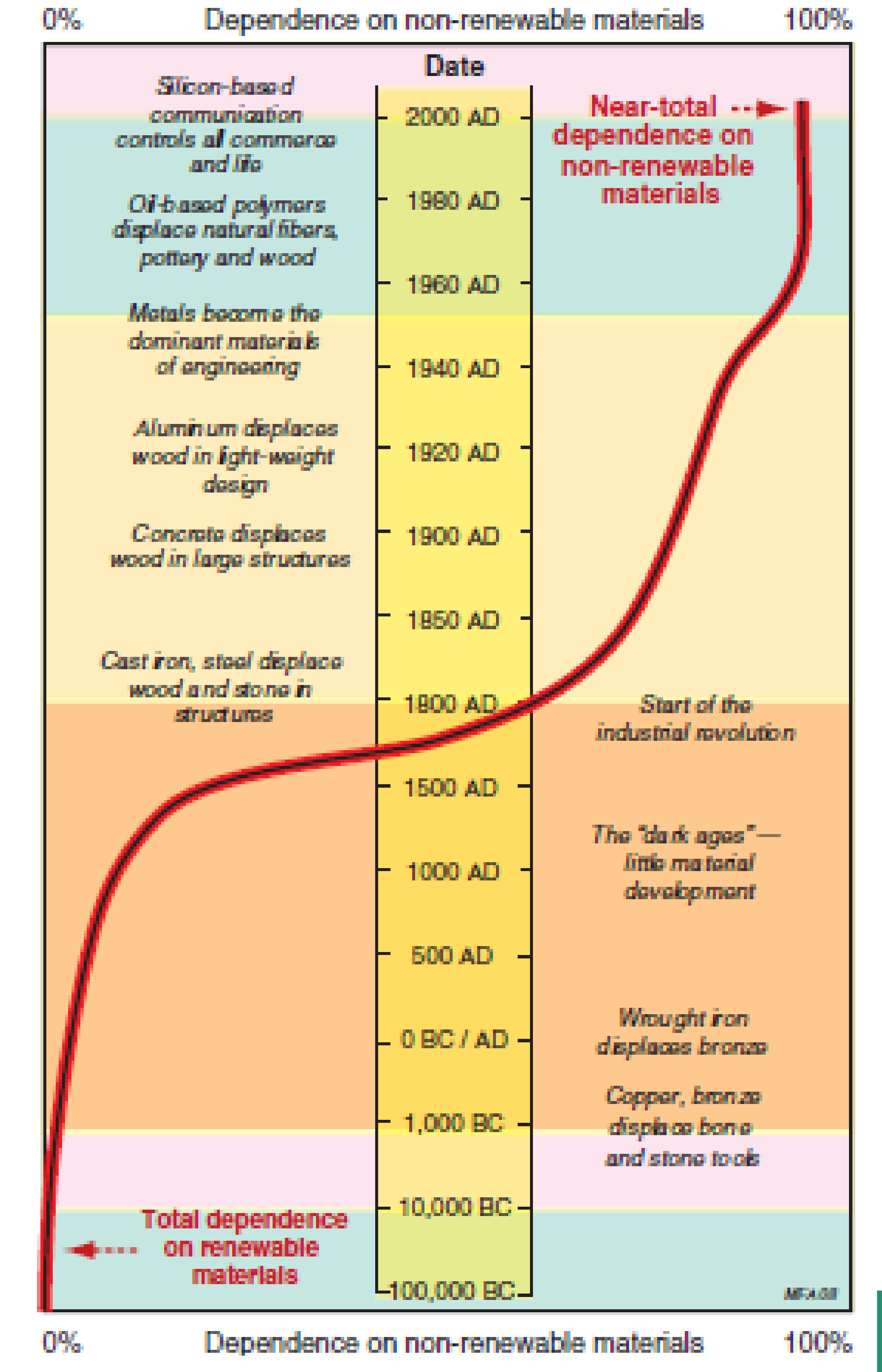
- Introduction
- The steps in materials selection
- Example: the underbody plate of a car

The Materials Library



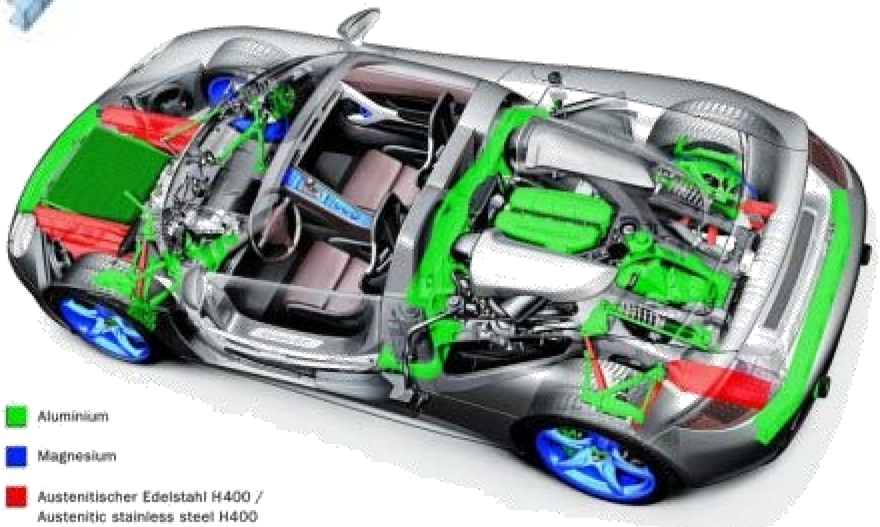
MMATENG

Dependence on Non-renewable Materials



A CAR

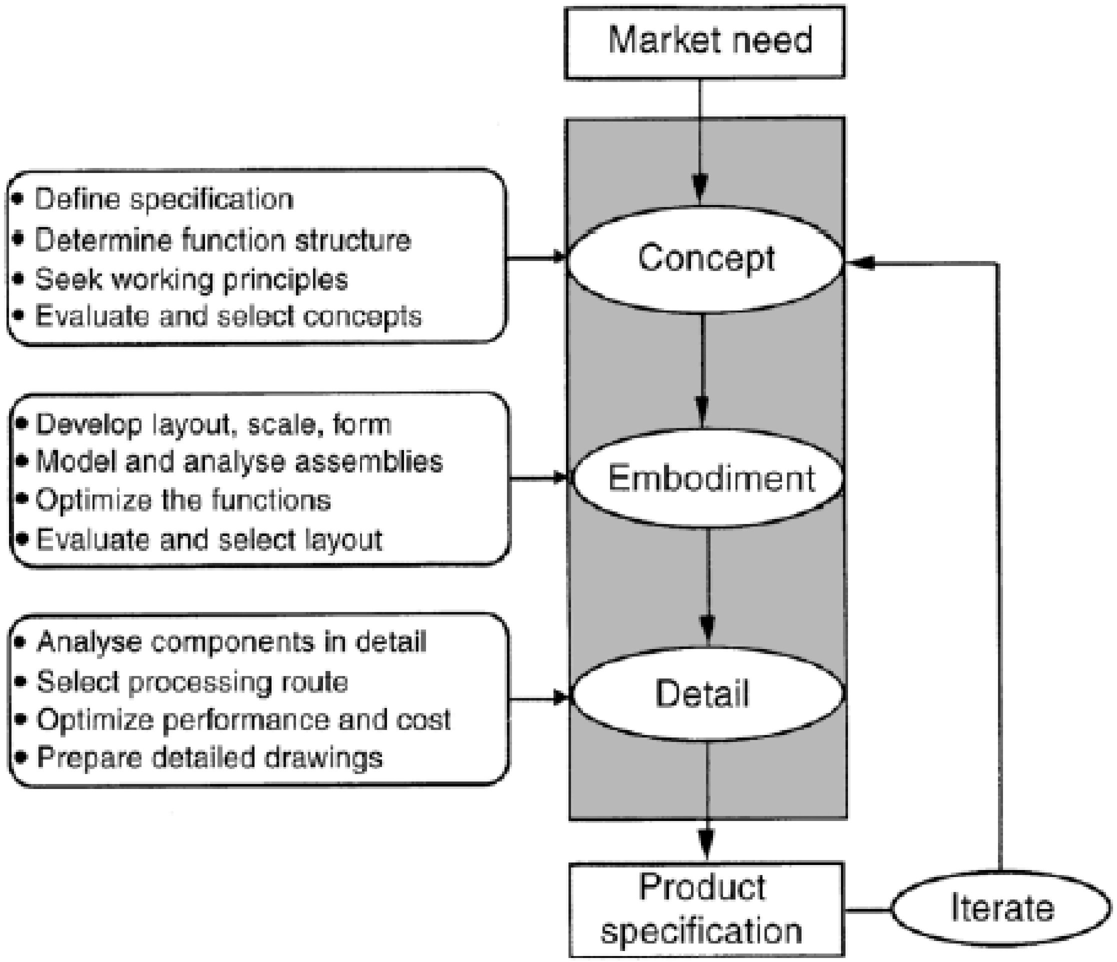
A light car


Aluminium
Magnesium
Austenitischer Edelstahl H400 /
Austenitic stainless steel H400

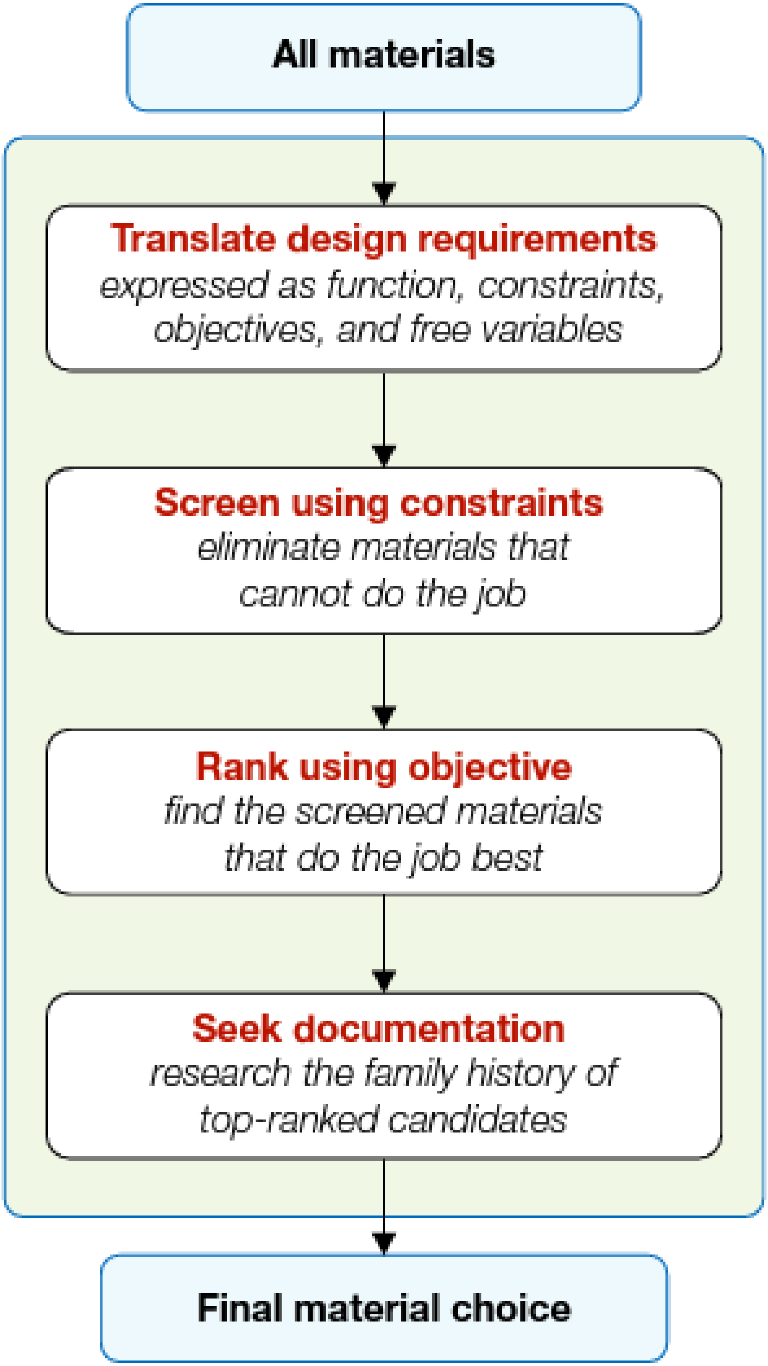
A cheap car

An environmentally friendly car

The design process



Steps



All materials
Translate design requirements
expressed as function, constraints, objectives, and free variables
Screen using constraints
eliminate materials that cannot do the job
Rank using objective
find the screened materials that do the job best
Seek documentation
research the family history of top-ranked candidates
Final material choice

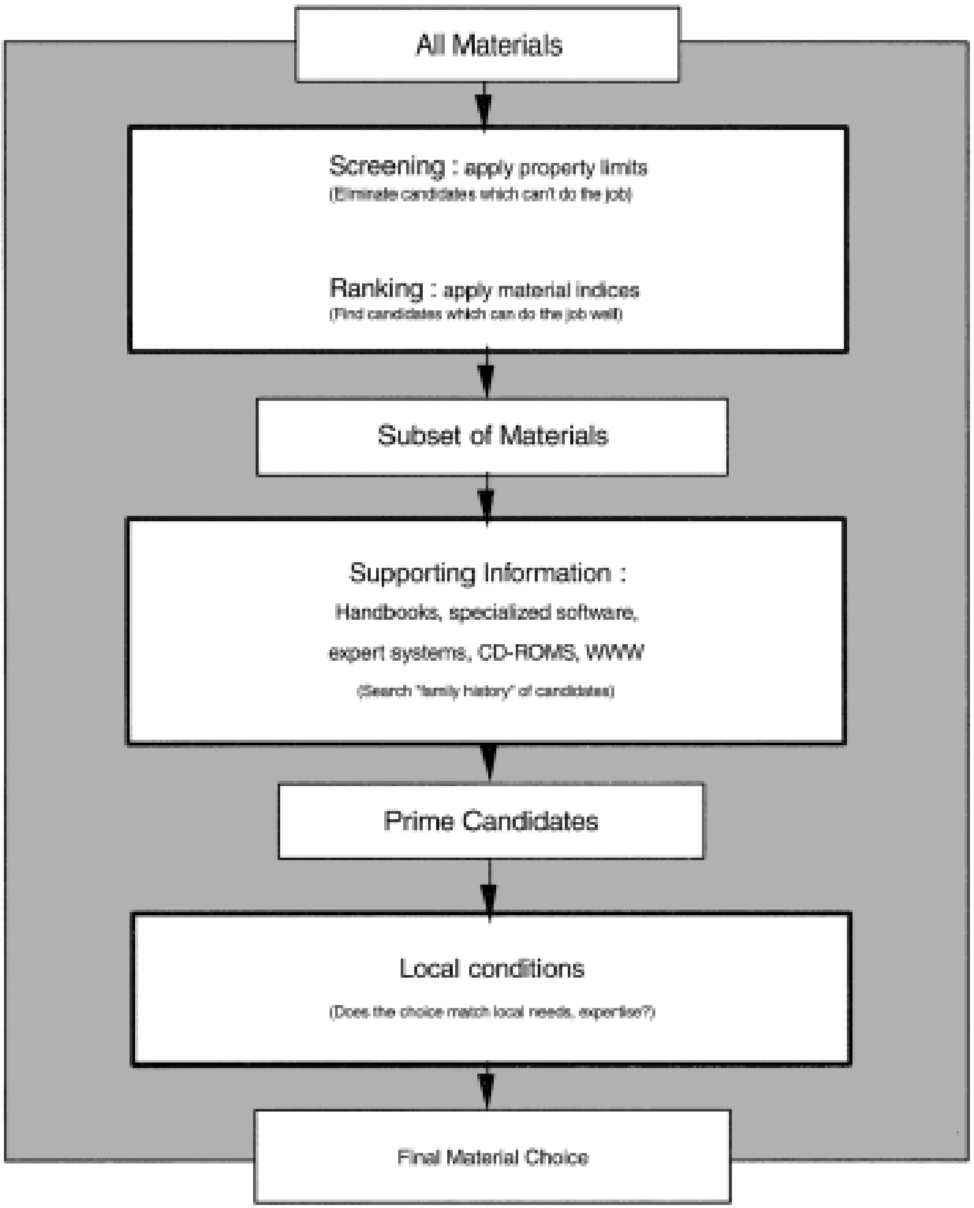


Fig. 5.3 The strategy for materials selection. The main steps are enclosed in bold boxes.

Brainstorm

- Gather:
  - o What is the purpose of the component? ➔ function?
  - o What can all play a role in the materials selection?
    - No restrictions
- Assess: what is important? What is not?
  - o Need to have: primary elements
  - o Nice to have: secondary
  - o Others
- What is our design focus (goal)?

Translation

Table 5.1 Function, Constraints, Objectives, and Free Variables

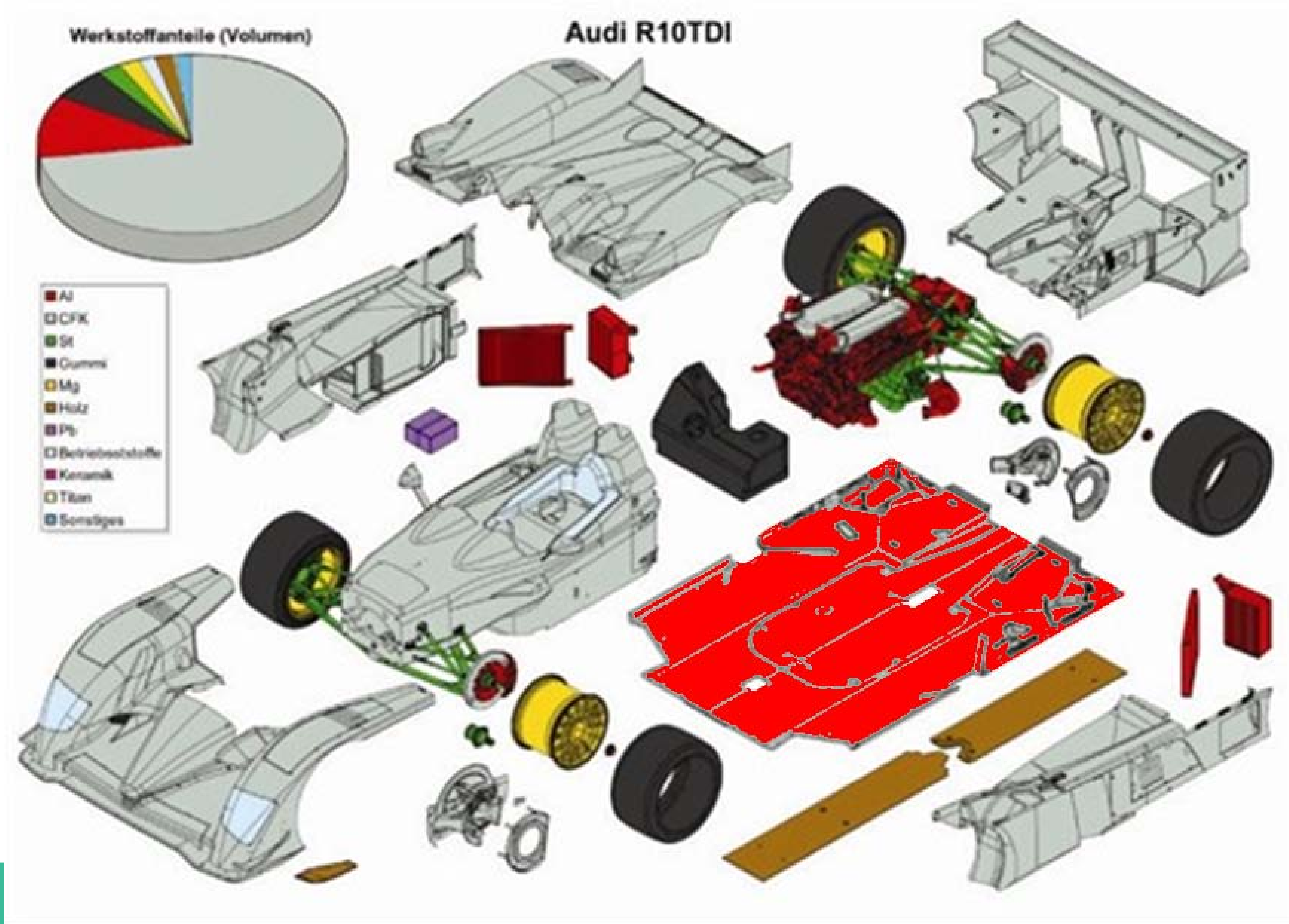
Function	What does the component do?
Constraints*	What nonnegotiable conditions must be met? What negotiable but desirable conditions must be met?
Objectives	What is to be maximized or minimized?
Free variable	Which parameters of the problem is the designer free to change?

**It is sometimes useful to distinguish between "hard" and "soft" constraints. Stiffness and strength might be absolute requirements (hard constraints); cost might be negotiable (soft constraint).*

screening

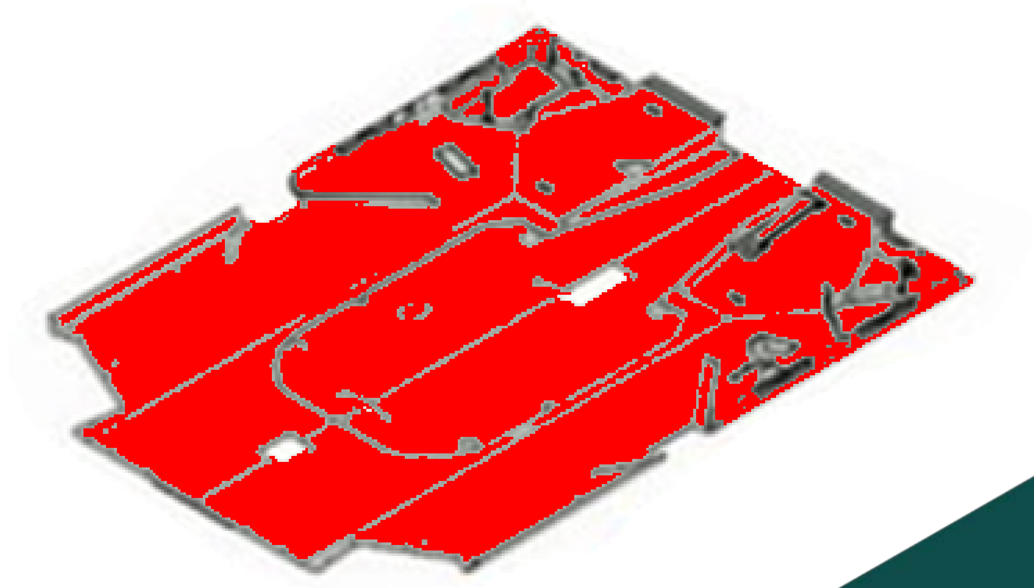
ranking

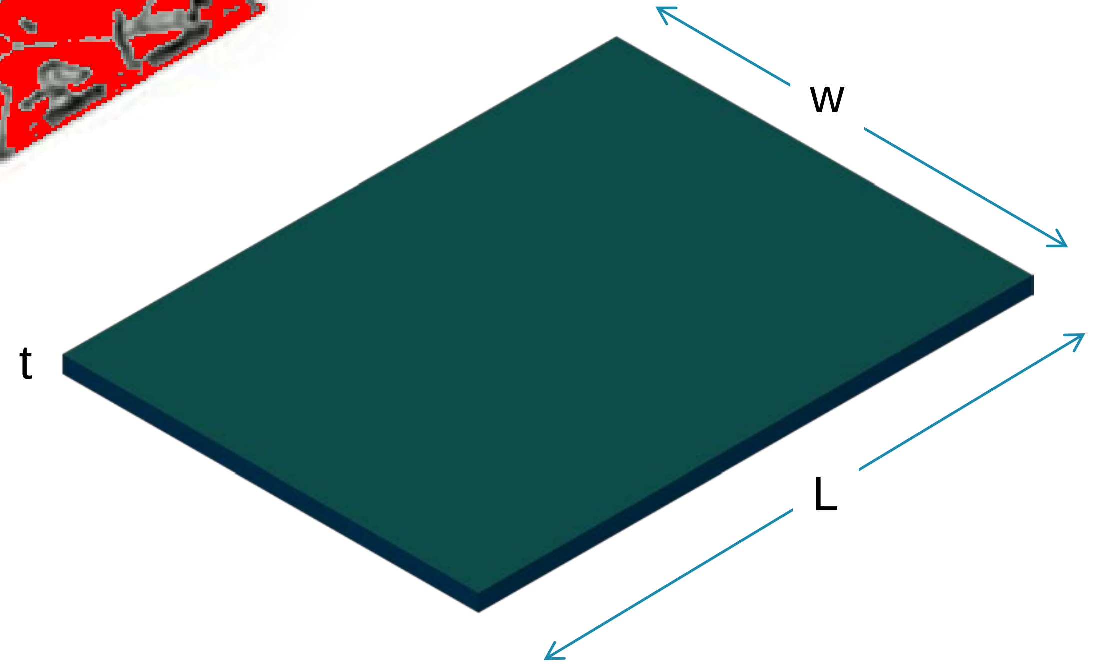
Our car: function



Objectives

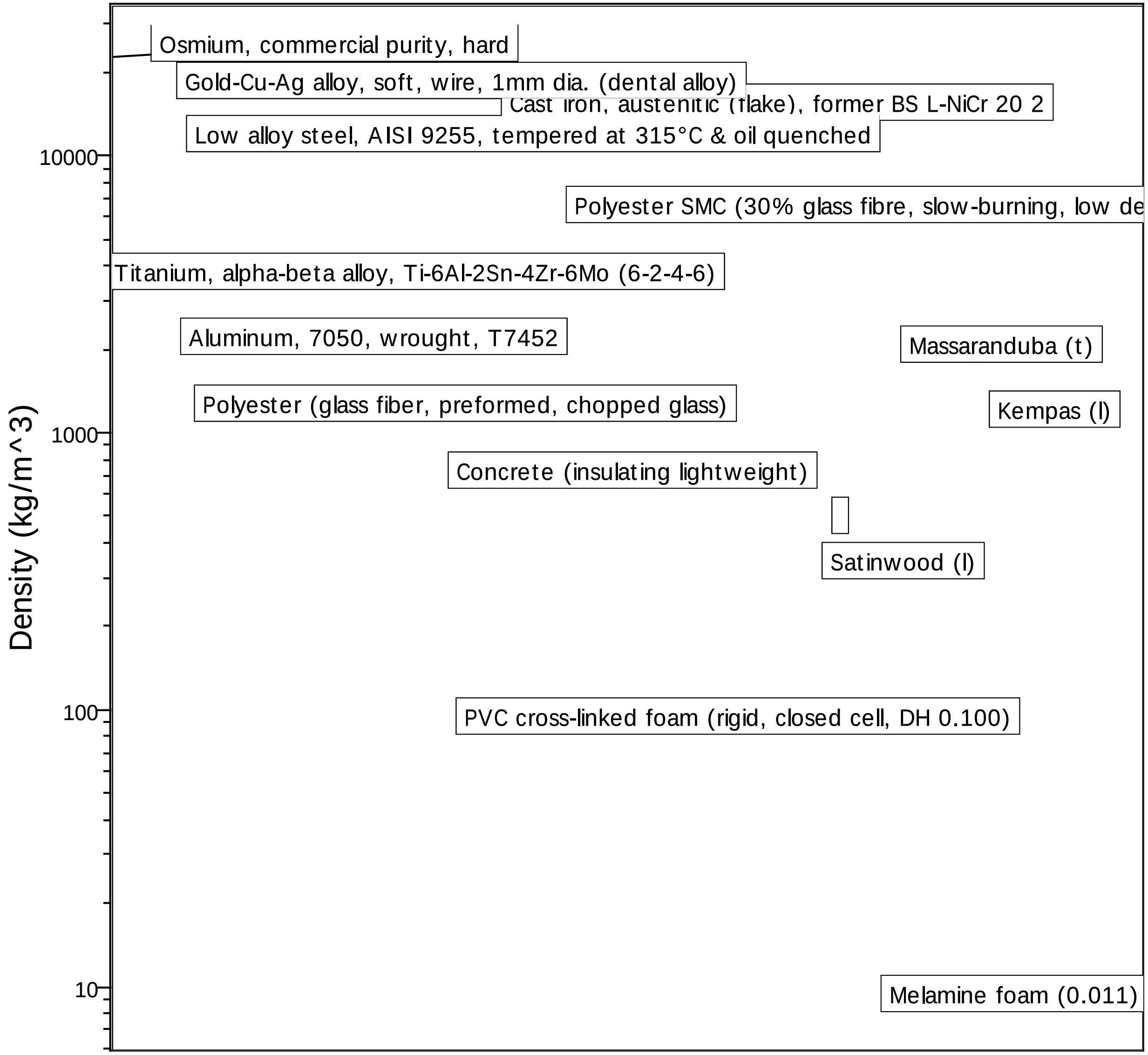
- Minimise weight/cost/environmental impact of bottom plate of car





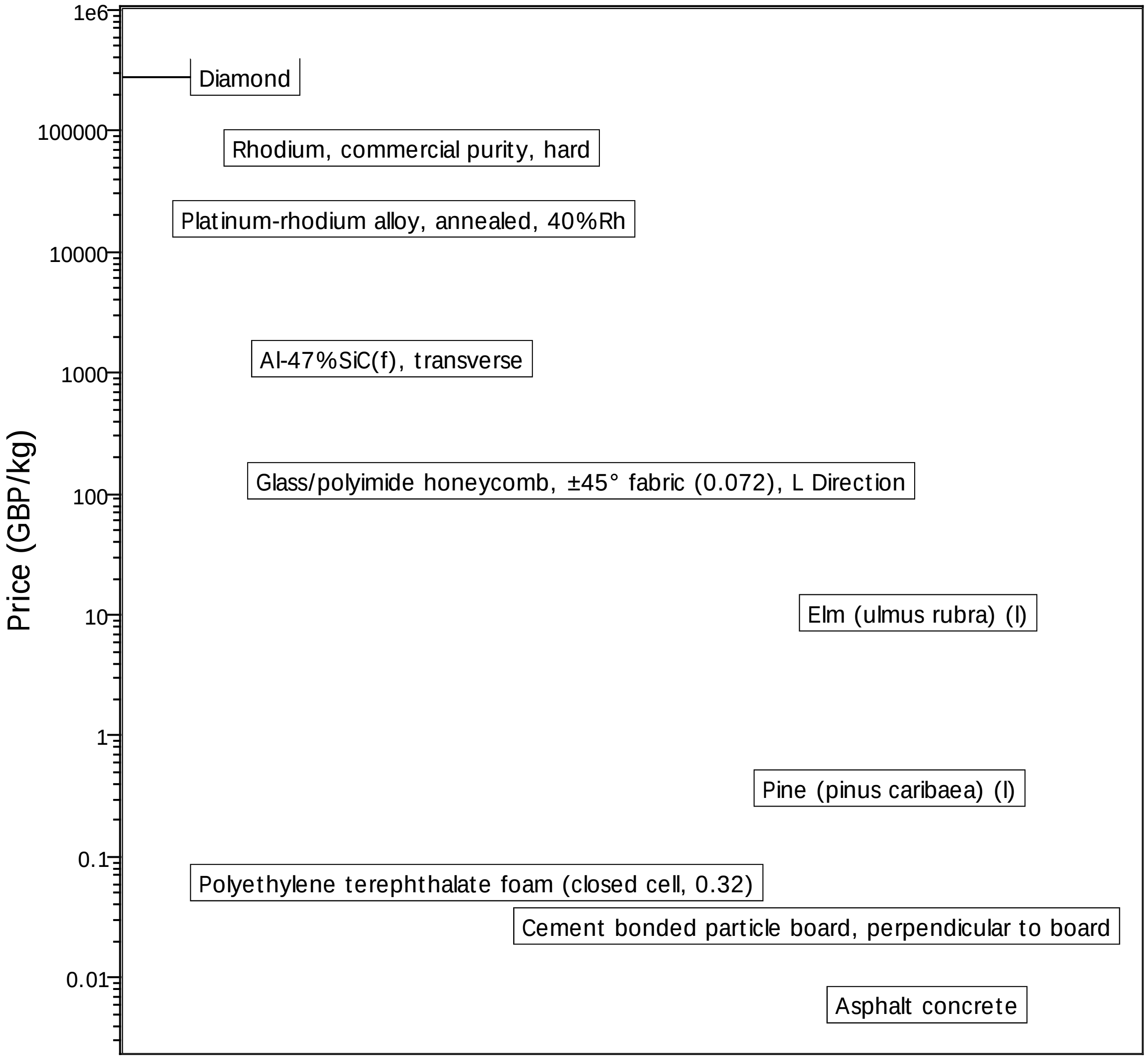
Objective 1: minimize mass

$$m = \rho \cdot L \cdot w \cdot t$$



Objective 2: minimize material cost

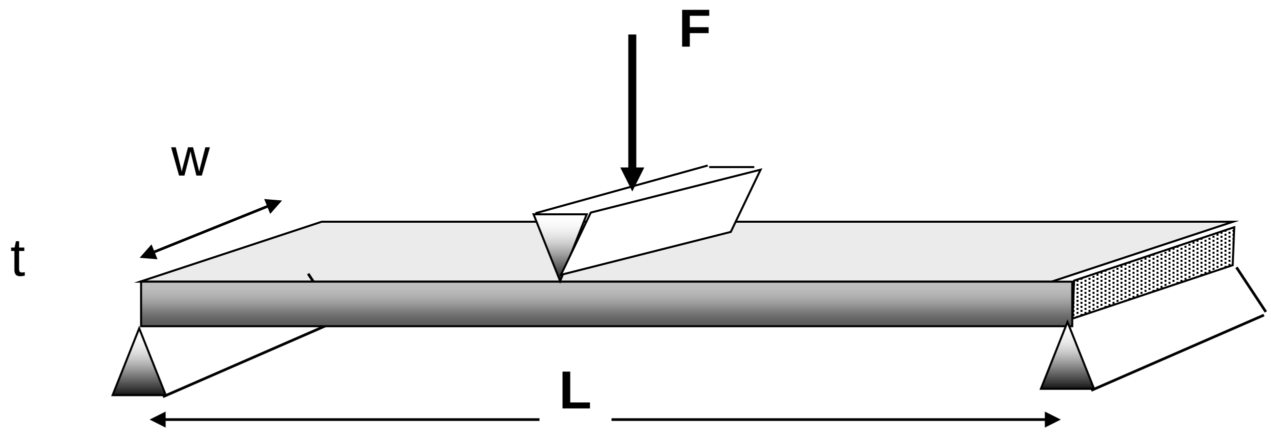
$$C = C_m \cdot m$$
$$= C_m \cdot \rho \cdot L \cdot w \cdot t$$



Constraint 1

=> Limited elastic deformation

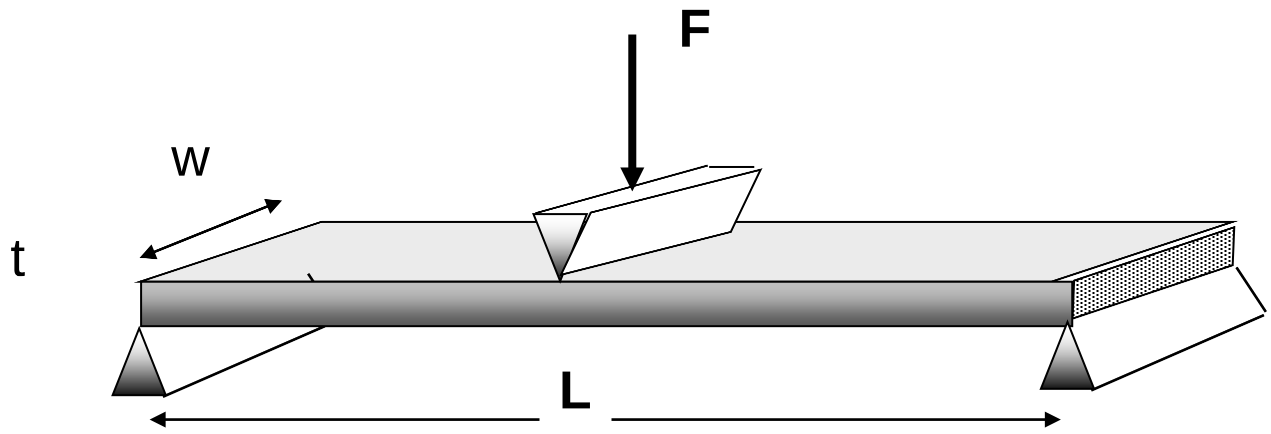
$$S = \frac{F}{\delta} \geq C_1 \frac{EI}{L^3} \qquad I = \frac{wt^3}{12}$$



Constraint 2

=> No plastic deformation or failure

$$\sigma = C\frac{FL}{Z} = C'\frac{FL}{wt^2} \leq \sigma_f$$



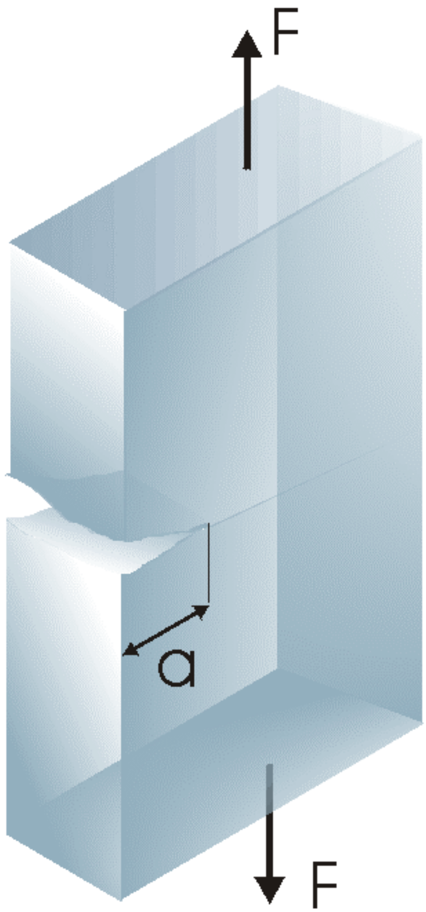
Constraint 3

=> No brittle fracture

$$K_{Ic} \geq K = Y\sigma\sqrt{\pi a}$$

Maximum = yield strength

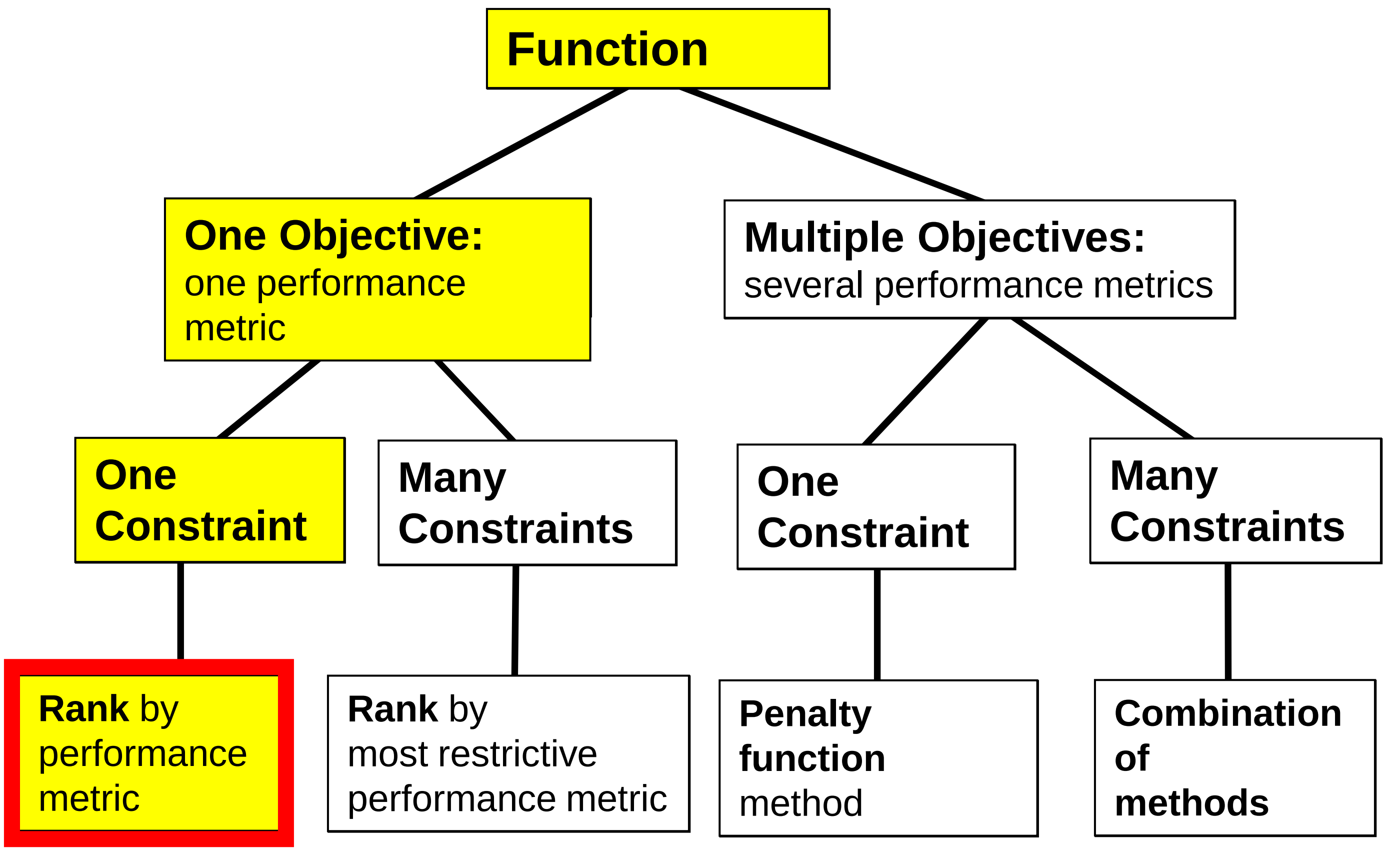
Determined by defect detection limit



Simplest case

Simplest case:

Design with one objective, meeting a single constraint



Free variable(s)

- L & w are determined by car dimensions
- => **constants**

- t (thickness of bottom plate) can be varied
- => **free variable**

Case 1 A light car – stiffness constraint

- Eliminate the free variable by combining objective and constraint function

- m = **ρ** x L x w x **t**

$$S = \frac{F}{\delta} \geq C_1 \frac{\boxed{E} \cdot I}{L^3}$$

$$I = \frac{w \boxed{t^3}}{12}$$

Load

$$m \leq L^2 \sqrt[3]{\frac{12w^2}{C_1}} \cdot \sqrt[3]{\frac{F}{\delta}} \cdot \frac{\rho}{\sqrt[3]{E}}$$

Geometry **Material Properties**

Material Index MI

$$MI = \frac{\rho}{\sqrt[3]{E}} \min$$

$$MI' = \frac{\sqrt[3]{E}}{\rho} \max$$

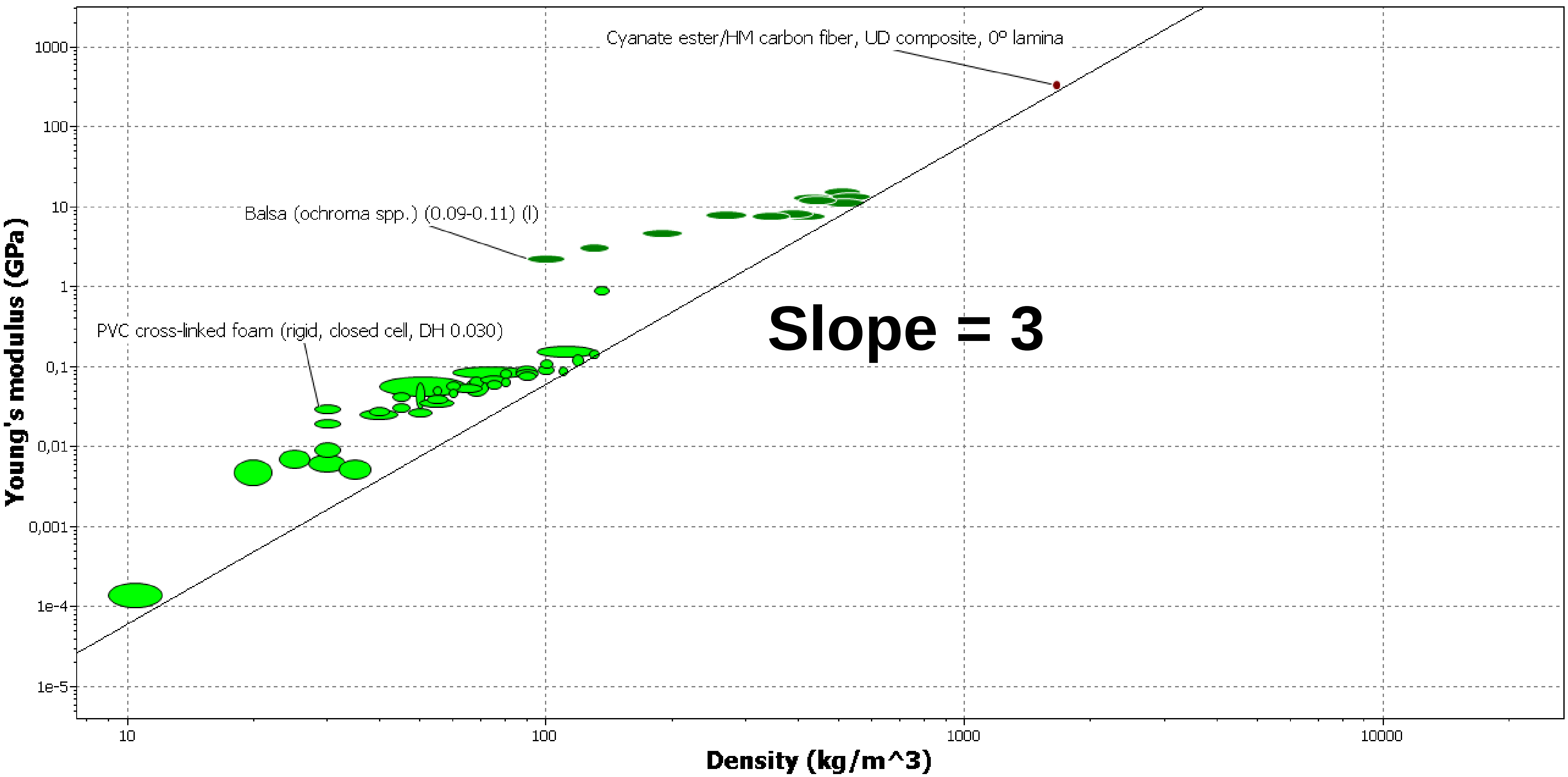
Log(E)-3log(ρ) = 3log(MI')

Log(E) = 3log(ρ) + 3log(MI')

Y = mX +Q

Slope = 3

Material Index



List of Materials Passing

Name	Stage 1: Index
Balsa (ochroma spp.) (0.09-0.11) (l)	0.0132
Balsa (ochroma spp.) (0.12-0.14) (l)	0.0112
PVC cross-linked foam (rigid, closed cell, DH 0.030)	0.0104
PVC cross-linked foam (rigid, closed cell, KR 0.030)	0.00906
Balsa (ochroma spp.) (0.17-0.21) (l)	0.00885
PS foam (closed cell, 0.020)	0.00852
PVC cross-linked foam (rigid, closed cell, DH 0.045)	0.00785
PS foam (closed cell, 0.025)	0.00774
Polymethacrylimide foam (rigid, 0.051)	0.00765
PVC cross-linked foam (rigid, closed cell, KR 0.040)	0.00764
Balsa (l) (ld)	0.00744
PVC cross-linked foam (rigid, closed cell, AC 0.040)	0.00743
Glass foam (0.13)	0.00718
PVC cross-linked foam (rigid, closed cell, KR 0.045)	0.00706
Carbon foam (reticulated, vitreous)(0.05)	0.00705
PS foam (closed cell, 0.030)	0.00703
Styrene acrylonitrile foam (closed cell, 0.055)	0.00675

FOAMS and WOOD!

Case 2 A cheap car – strength constraint

- Eliminate the free variable by combining objective and constraint function

$$C = \boxed{C_m \cdot \rho} \cdot L \cdot w \cdot \boxed{t}$$

$$\boxed{\sigma_f} \geq C' \frac{FL}{w\boxed{t^2}}$$

$$C \leq \underbrace{\sqrt{C' \cdot w \cdot L^3}}_{\text{Geometry}} \cdot \overbrace{\sqrt{F}}^{\text{Load}} \cdot \underbrace{\frac{C_m \rho}{\sqrt{\sigma_f}}}_{\text{Material Properties}}$$

Material Index

$$\frac{C_m \rho}{\sqrt{\sigma_f}} \min$$

$$\frac{\sqrt{\sigma_f}}{C_m \rho} \max$$

$\mathrm{Log}(\sigma_f) - 2\log(C_m \rho) = 2\log(MI)$

$\mathrm{Log}(\sigma_f) = 2\log(C_m \rho) + 2\log(MI)$

$$Y = mX + Q$$

Slope = 2

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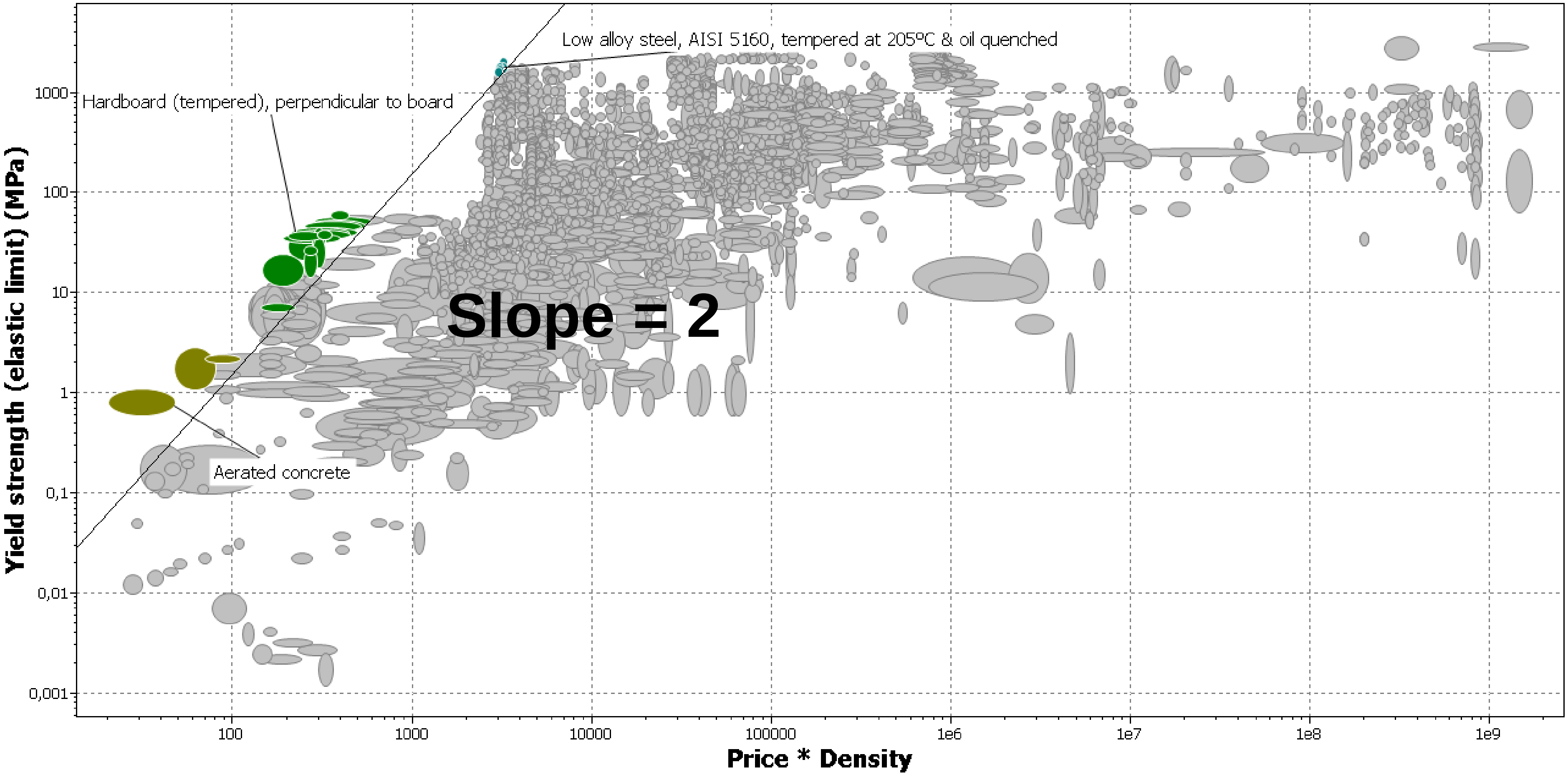

List of materials passing

Name	Stage 2: Index
Aerated concrete	0,029
Hardboard (tempered), perpendicular to board	0,0242
Hardboard (standard), perpendicular to board	0,0216
Concrete (structural lightweight)	0,0216
Redwood (sequoia sempervirens (young)) (l)	0,0215
Hardboard (tempered), parallel to board	0,0214
Fir (abies procera) (l)	0,0206
Spruce (picea rubens) (l)	0,0198
Oak (quercus falcata var. pagodifolia) (l)	0,0197
Spruce (picea abies) (l)	0,0191
Fiberboard, hard, perpendicular to board	0,0191
Plywood (3 ply, beech), parallel to face layer	0,019
Plywood (5 ply, beech), parallel to face layer	0,019
Plywood (7 ply, beech), parallel to face layer	0,019
Fiberboard, extra hard, perpendicular to board	0,0188
Pine (pinus spp.) (l)	0,0185
Douglas fir (pseudotsuga menziesii (northern)) (l)	0,0182
Larch (larix decidua) (l)	0,0177
Concrete (super sulfate cement)	0,0169

WOOD and CONCRETE

Case 3 A cheap car – no brittle fracture

- Eliminate the free variable by combining objective and constraint function

$$C = \boxed{C_m \cdot \rho} \cdot L \cdot w \cdot \boxed{t}$$

$$\boxed{K_{Ic}} \geq Y \sigma \sqrt{\pi a}$$

$$\sigma = C' \frac{FL}{w \boxed{t^2}}$$

$$C \leq \underbrace{\sqrt{YC' \cdot w \cdot L^3 \sqrt{\pi a}}}_{\text{Geometry}} \cdot \overbrace{\sqrt{F}}^{\text{Load}} \cdot \underbrace{\frac{C_m \rho}{\sqrt{K_{Ic}}}}_{\text{Material Properties}}$$

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Tempus

Material Index

$$\frac{C_m \rho}{\sqrt{K_{Ic}}} \min$$

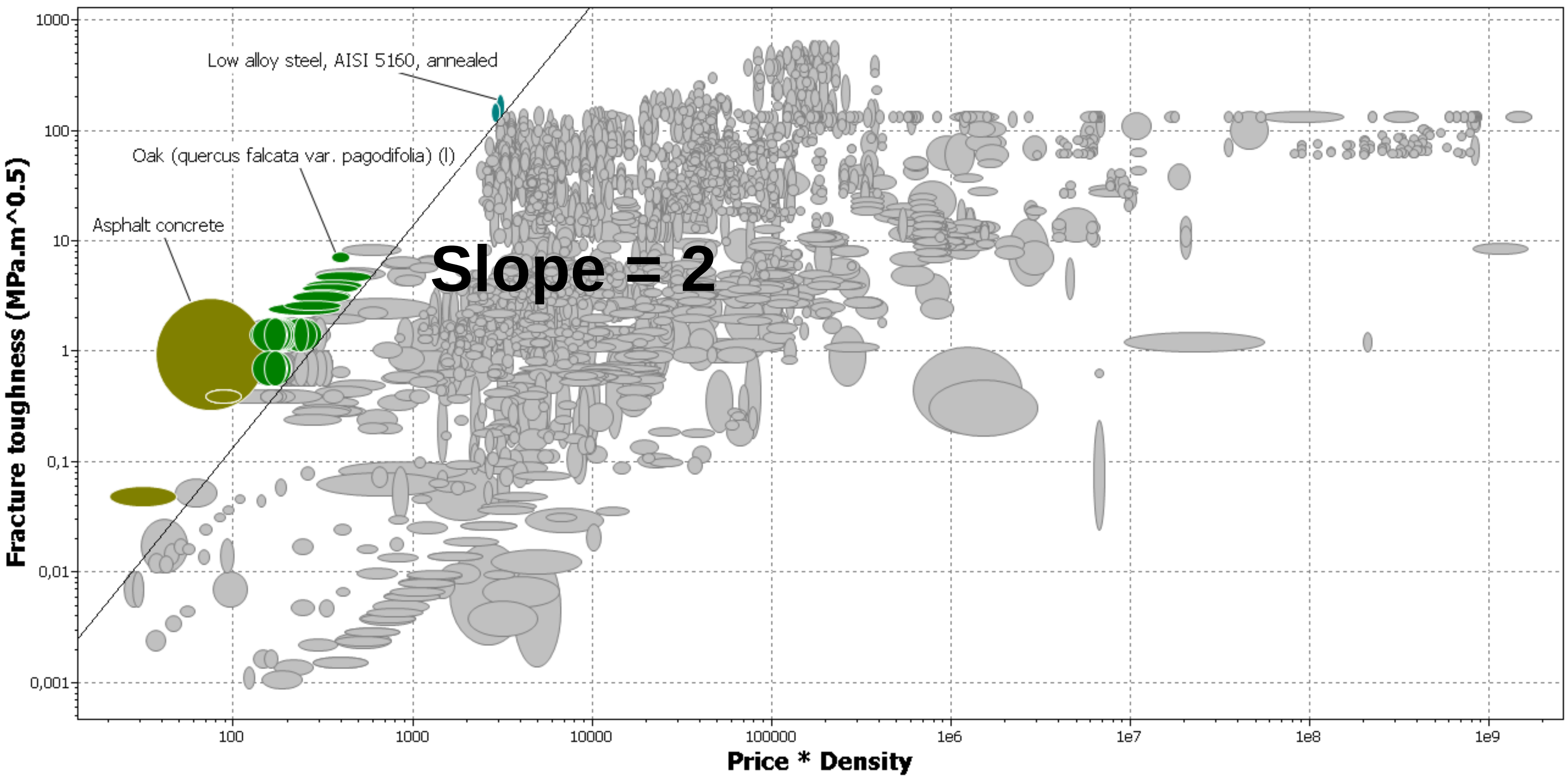
$$\frac{\sqrt{K_{Ic}}}{C_m \rho} \max$$

Log(K$_{Ic}$)-2log(C$_m$ρ) = 2log(MI)

Log(K$_{Ic}$) = 2log(C$_m$ρ) + 2log(MI)

Y = mX +Q

Slope = 2



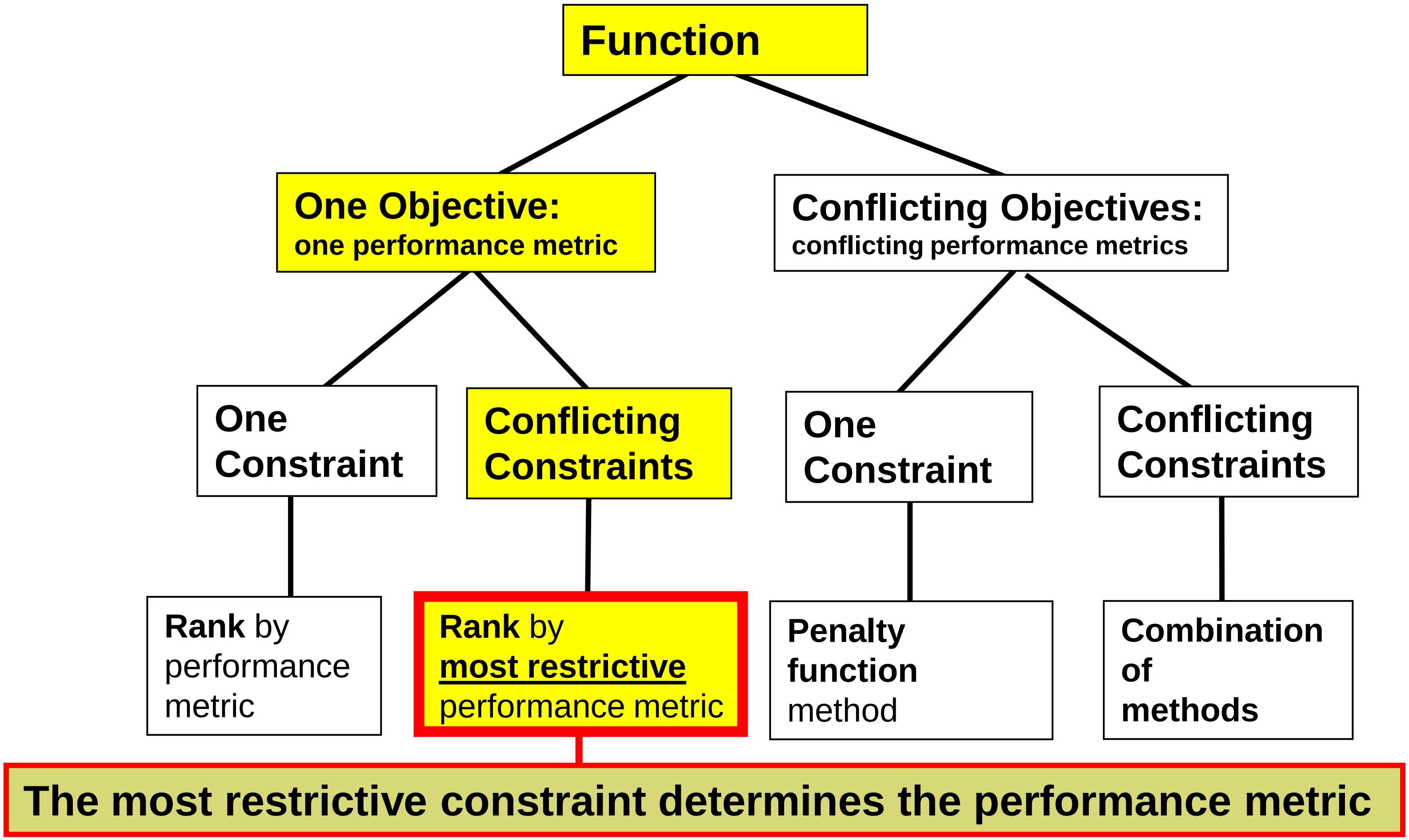
Low alloy steel, AISI 5160, annealed
Oak (quercus falcata var. pagodifolia) (l)
Asphalt concrete
Slope = 2
Fracture toughness (MPa.m^0.5)
Price * Density
1000
100
10
1
0,1
0,01
0,001
100
1000
10000
100000
1e6
1e7
1e8
1e9

List of materials passing

Name	Stage 2: Index
Aerated concrete	0,029
Hardboard (standard), perpendicular to board	0,0216
Redwood (sequoia sempervirens (young)) (l)	0,0215
Fir (abies procera) (l)	0,0206
Spruce (picea rubens) (l)	0,0198
Oak (quercus falcata var. pagodifolia) (l)	0,0197
Spruce (picea abies) (l)	0,0191
Pine (pinus spp.) (l)	0,0185
Larch (larix decidua) (l)	0,0177
Concrete (super sulfate cement)	0,0169
Wood chipboard, type C1, parallel to board	0,0167
Wood chipboard, type C1A, parallel to board	0,0159
Wood chipboard, type C3, parallel to board	0,0158
Gypsum bonded particleboard, parallel to board	0,0156
Wood chipboard, type C1, perpendicular to board	0,0152
Wood chipboard, type C1A, perpendicular to board	0,0145
Wood chipboard, type C3, perpendicular to board	0,0144
Palm (0.35)	0,0142
Gypsum bonded particleboard, perpendicular to board	0,0142

WOOD

One notch up in complexity: Single objective / Multiple constraints



Light car
stiff and strong

- Function: underbody panel
- Constraints: L and w known
  must not deform too much
  must not yield or break
- Objective: minimal mass
- Free variables panel thickness t
  choice of material

$$S = \frac{F}{\delta} \geq C_1 \frac{E \cdot wt^3}{12L^3}$$

$$\sigma_f \geq C \frac{6FL}{wt^2}$$

$$m = \rho \cdot L \cdot w \cdot t$$

Performance metrics

$$S \geq C_1 \frac{E \cdot wt^3}{12L^3} \qquad m = \rho \cdot L \cdot w \cdot t \qquad \sigma_f \geq C \frac{6FL}{wt^2}$$

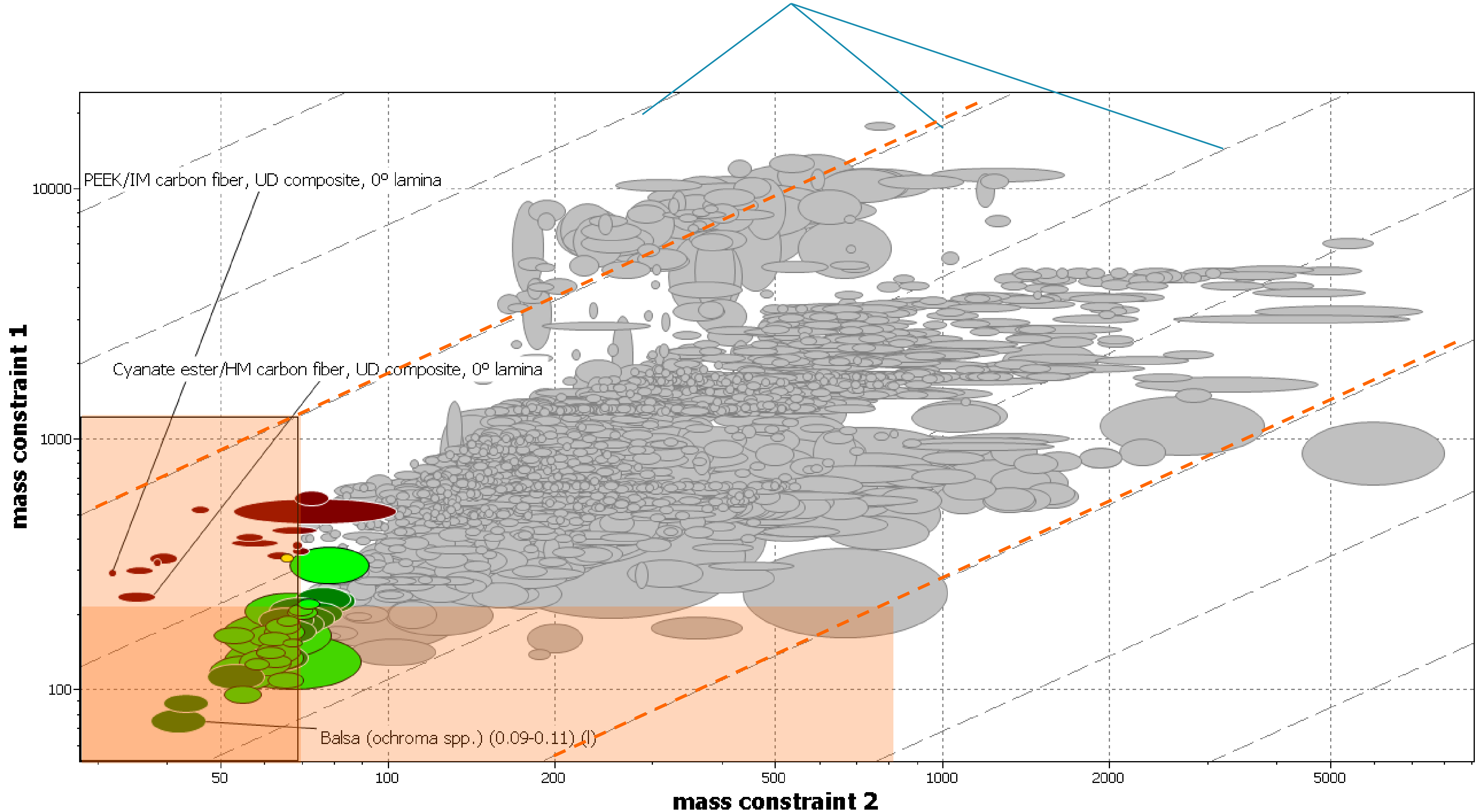
$$m_1 \leq L^2 \sqrt[3]{\frac{12w^2}{C_1}} \cdot \sqrt[3]{\frac{F}{\delta}} \cdot \boxed{\frac{\rho}{\sqrt[3]{E}}} \qquad m_2 \leq \sqrt{6C \cdot w \cdot L^3} \cdot \sqrt{F} \cdot \boxed{\frac{\rho}{\sqrt{\sigma_f}}}$$

M_1 M_2

$$M_1 = \boxed{C' \sqrt[6]{\frac{F\delta^2}{wL^3}}} \cdot M_2$$

Coupling constant

Coupling constant



One more notch up in complexity: Conflicting objectives / one constraint

- **Function**
  - **One Objective:** **one performance metric**
    - **One Constraint**
      - **Rank** by performance metric
    - **Multiple Constraints**
      - **Rank** by **most restrictive** performance metric
  - **Conflicting Objectives:** **conflicting performance metrics**
    - **One Constraint**
      - **Penalty function** method
    - **Multiple Constraints**
      - **Combination of methods**

The highest penalty function determines the performance metric

Conflicting objectives

• Function:	underbody panel	$$S = \frac{F}{\delta} \geq C_1 \frac{E \cdot wt^3}{12L^3}$$
• Constraints:	L and w known must not deform too much	
• Objective:	minimal mass minimal thickness	$$m = \rho \cdot L \cdot w \cdot t$$
• Free variables	panel thickness t choice of material	

Performance metrics

$$m = \rho \cdot L \cdot w \cdot t \quad S \geq C_1 \frac{E \cdot wt^3}{12L^3}$$

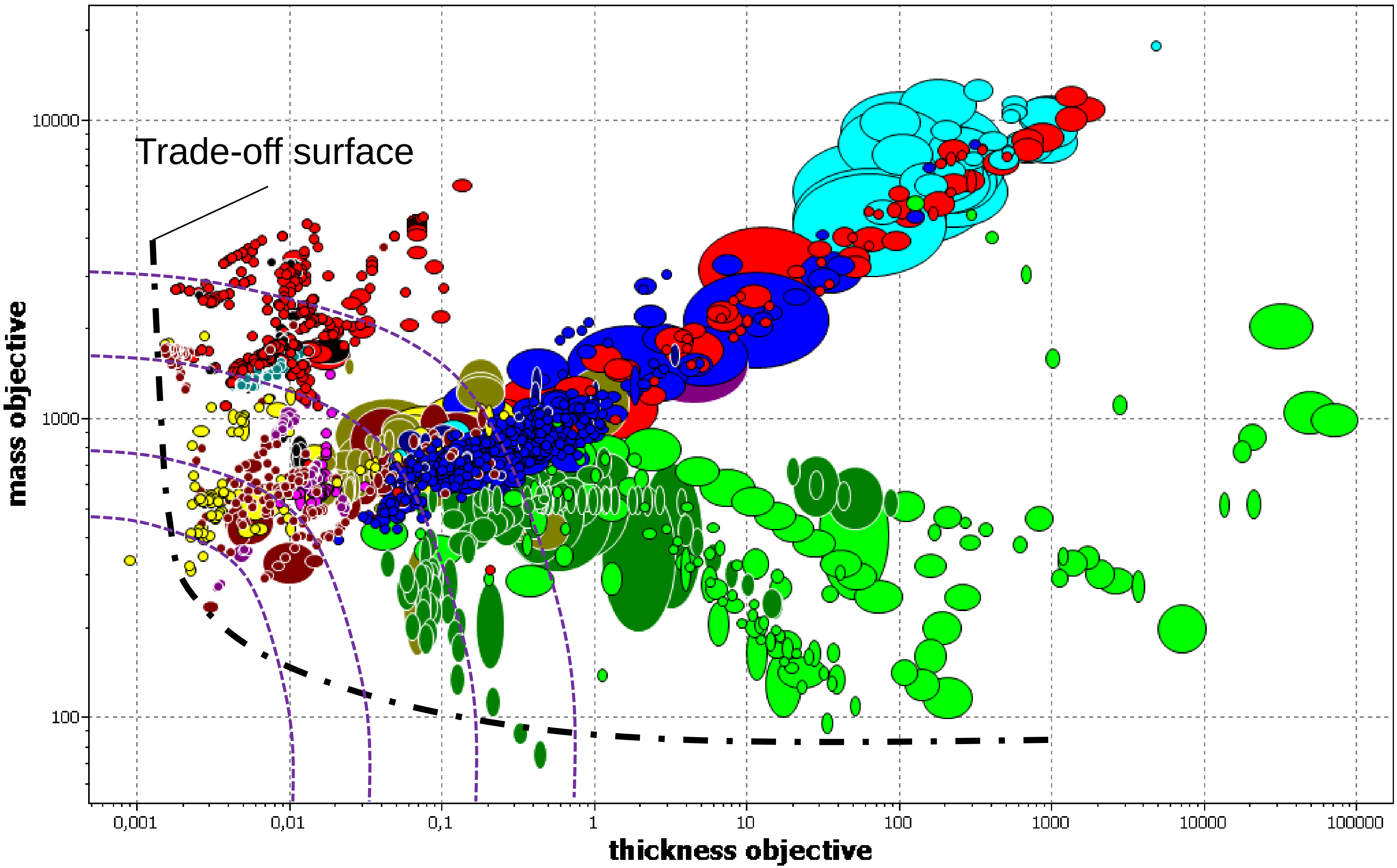
$$m \leq L^2 \sqrt[3]{\frac{12w^2}{C_1}} \cdot \sqrt[3]{\frac{F}{\delta}} \cdot \boxed{\frac{\rho}{\sqrt[3]{E}}}$$

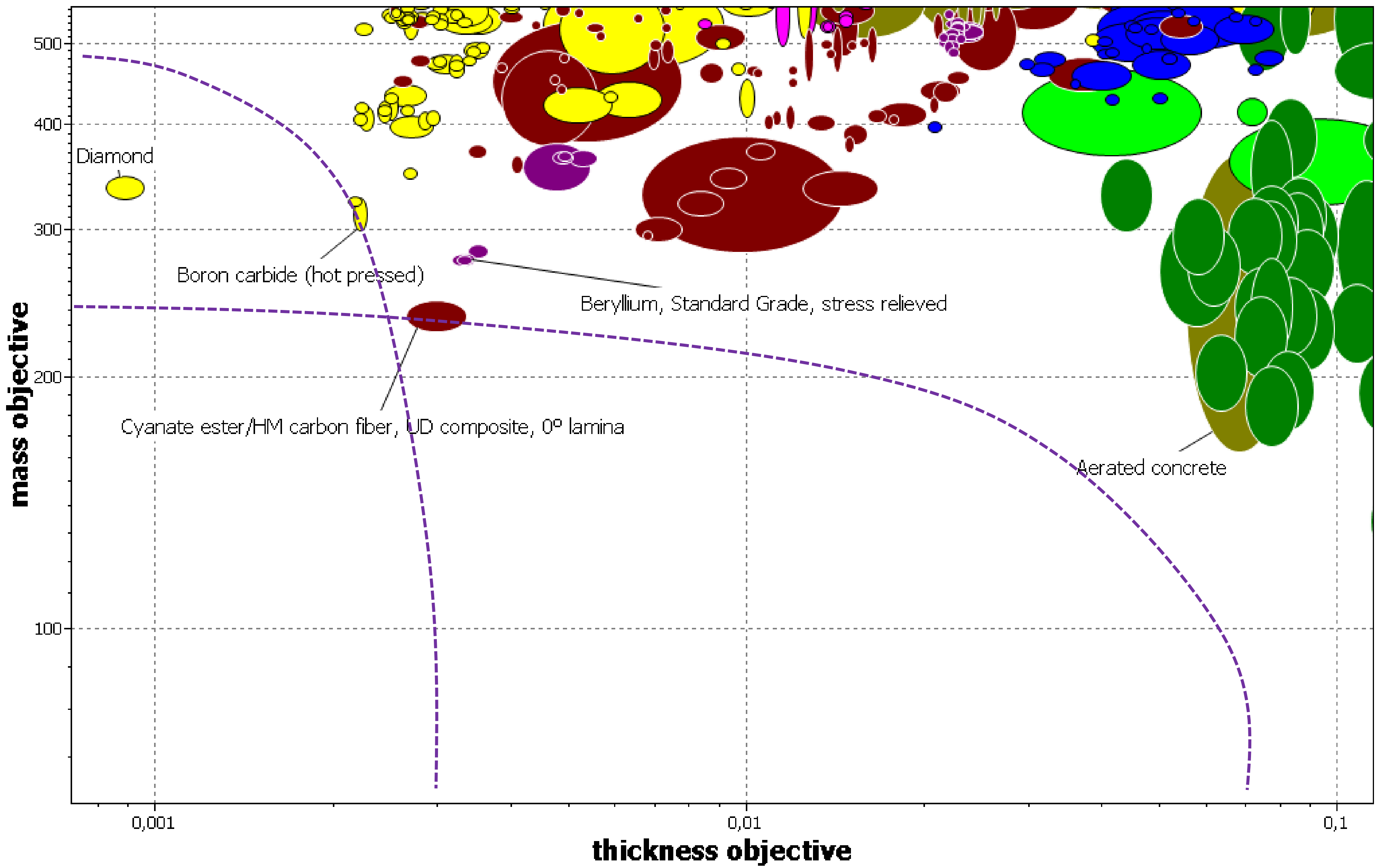
M_1

M_2

$$t \leq \sqrt[3]{\frac{12S}{C_1 w}} L \cdot \boxed{\frac{1}{\sqrt[3]{E}}}$$

Penalty function $Z = \alpha_1 \cdot m + \alpha_2 \cdot t$


Trade-off surface
mass objective
thickness objective
10000
1000
100
0,001
0,01
0,1
1
10
100
1000
10000
100000


mass objective
thickness objective
500
400
300
200
100
0,001
0,01
0,1
Diamond
Boron carbide (hot pressed)
Beryllium, Standard Grade, stress relieved
Cyanate ester/HM carbon fiber, UD composite, 0º lamina
Aerated concrete

Conflicting objectives

- Function: underbody panel
- Constraints: L and w known
  must not deform too much
  E at least 5 GPa
- Objective: minimal mass
  minimal material cost
- Free variables panel thickness t
  choice of material

$$S = \frac{F}{\delta} \geq C_1 \frac{E \cdot wt^3}{12L^3}$$

$$m = \rho \cdot L \cdot w \cdot t$$

$$C = C_m \cdot \rho \cdot L \cdot w \cdot t$$

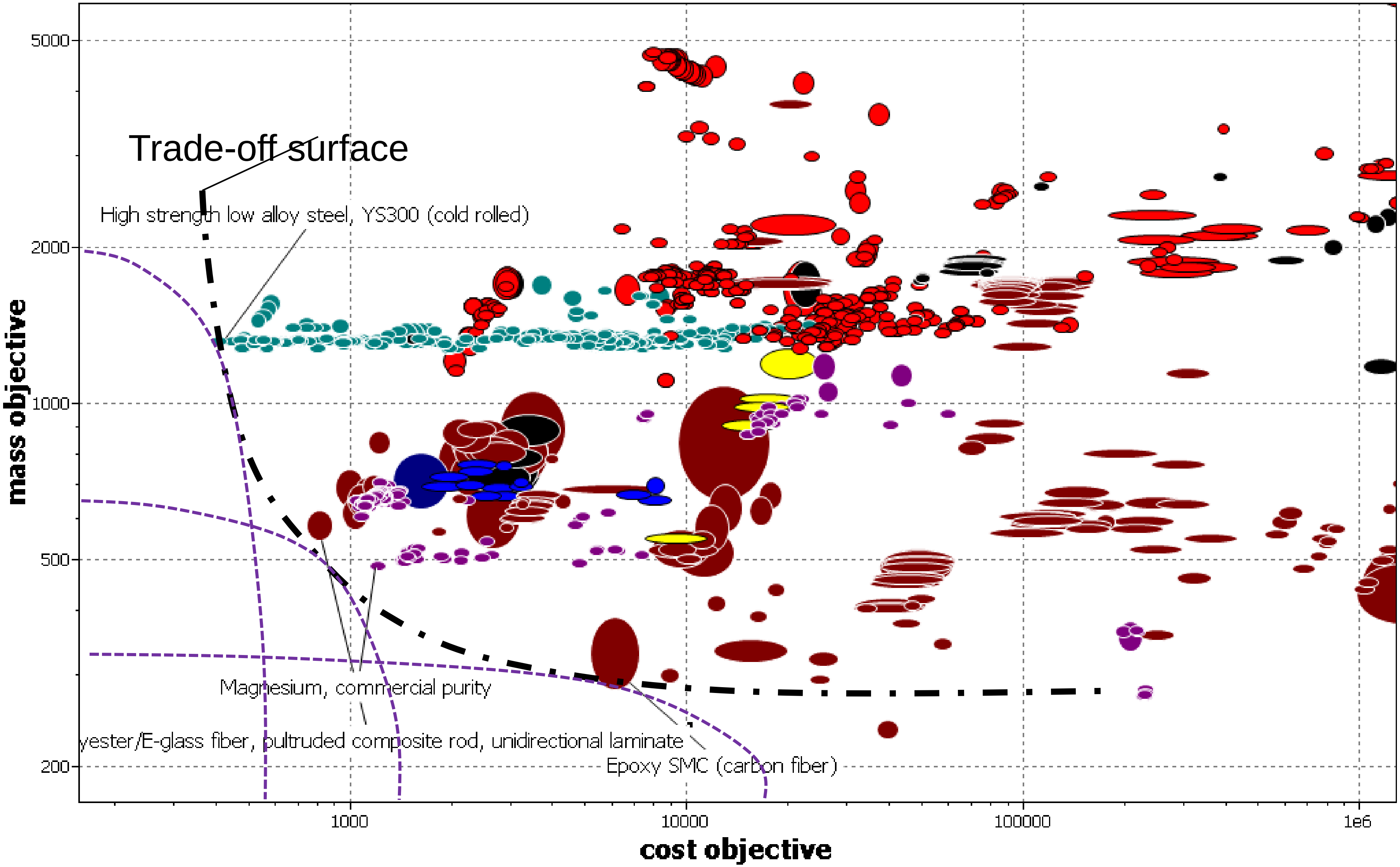
Performance metrics

$$m = \rho \cdot L \cdot w \cdot t \qquad S \geq C_1 \frac{E \cdot wt^3}{12L^3} \qquad C = C_m \cdot \rho \cdot L \cdot w \cdot t$$

$$m : \frac{\rho}{\sqrt[3]{E}} \min \qquad C : \frac{C_m \cdot \rho}{\sqrt[3]{E}} \min$$

Penalty function $$Z = \alpha \cdot m + C$$

CHEAP CAR LIGHT CAR



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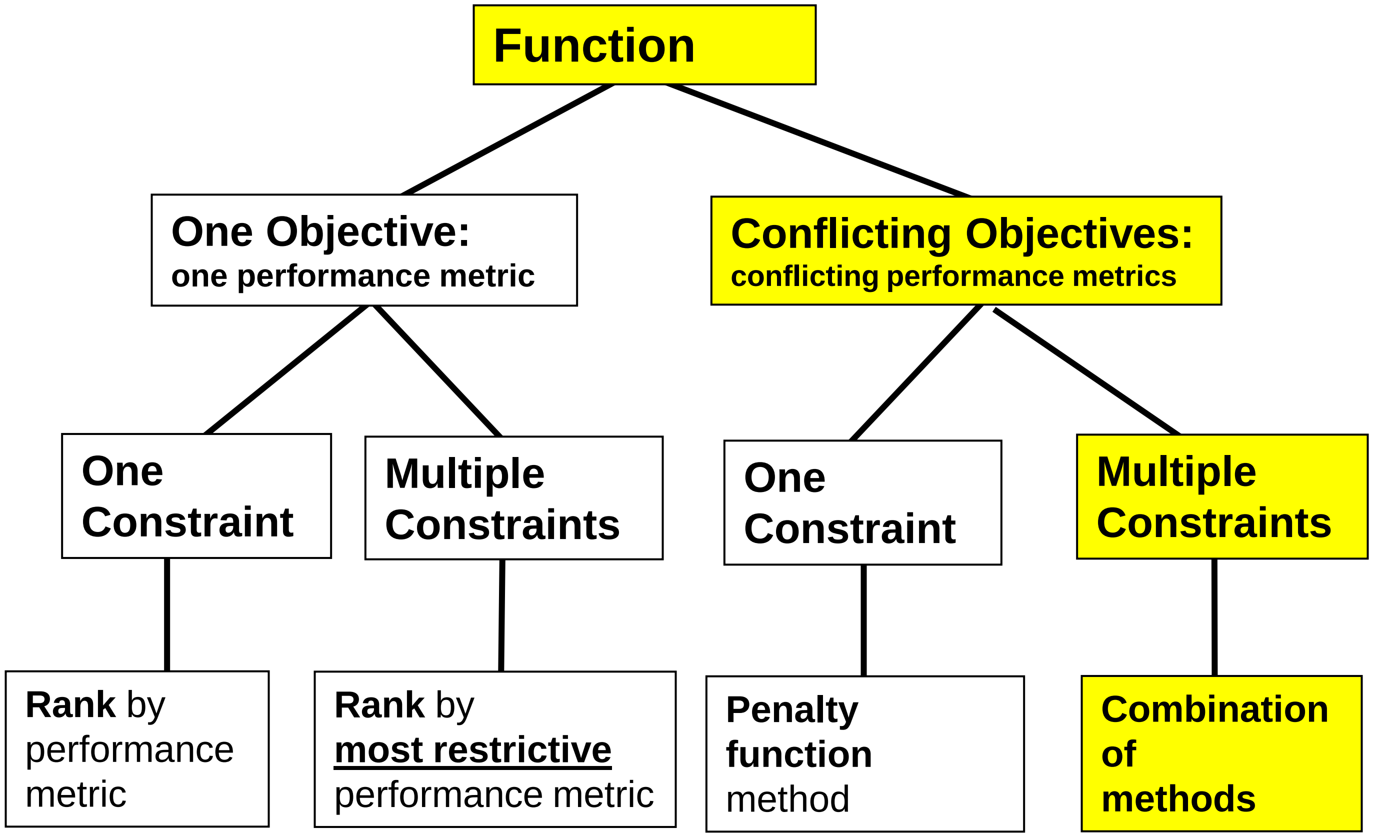
Exchange constants

(<u>Upper bounds to</u>) Exchange constants for mass saving in transport systems

Transport System: mass saving	α (€ per kg)
Family car (based on fuel saving)	**0.5 ~ 5**
Truck (based on payload)	**5 to 20**
Civil aircraft (based on payload)	**100 to 500**
Military aircraft (performance payload)	**500 to 1000**
Space vehicle (based on payload)	**3000 to 10000**

The ultimate challenge



The ultimate

• Function:	underbody panel
• Constraints:	L and w known must not deform too much E at least 5 GPa must not plastically deform or fail must not have brittle failure must resist to water
• Objective:	minimal mass minimal material cost minimal embodied energy
• Free variables	panel thickness t choice of material

The objectives

- minimal mass $m = \rho \cdot L \cdot w \cdot t$
- minimal material cost $C = C_m \cdot \rho \cdot L \cdot w \cdot t$
- minimal embodied energy $H = H_m \cdot \rho \cdot L \cdot w \cdot t$

The constraints

- Screening constraints
  E at least 5 GPa
  must resist to water

- Ranking constraints
  must not deform too much $$S \geq C_1 \frac{Ewt^3}{12L^3}$$
  must not plastically deform or fail $$\sigma_f \geq C \frac{6FL}{wt^2}$$
  must not have brittle failure $$K_{Ic} \geq Y\sigma\sqrt{\pi a}$$

Material index

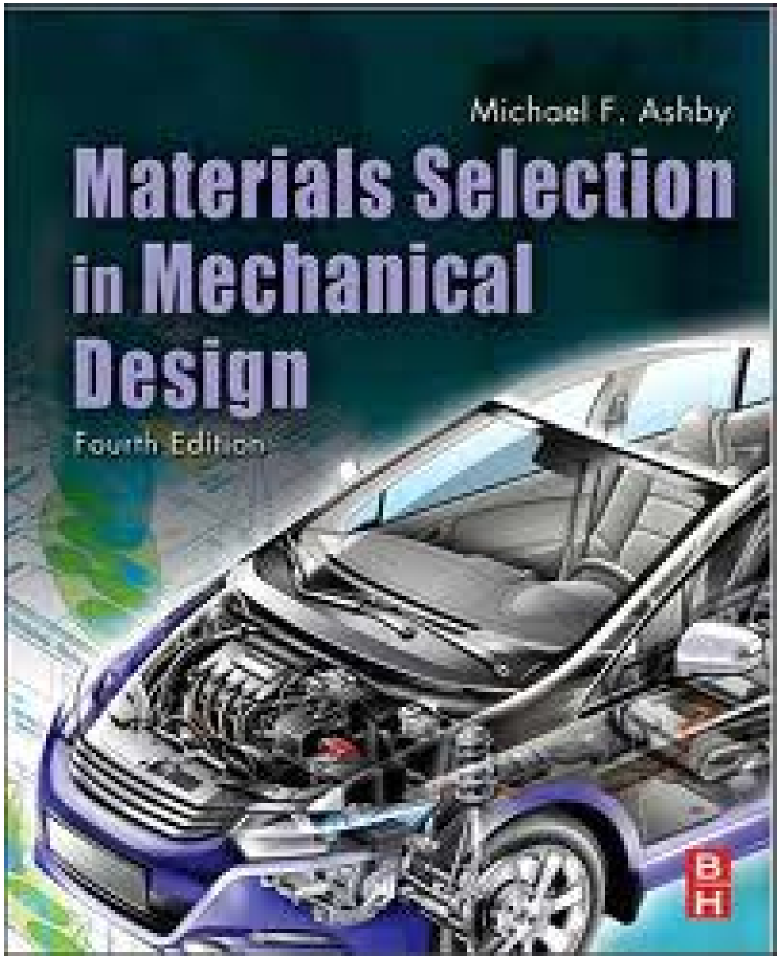
Objective	Constraint	Material index Mi
Minimum mass	Stiffness	$\rho / \sqrt[3]{E}$
Minimum mass	Strength	$\rho / \sqrt{\sigma_y}$
Minimum mass	Toughness	$\rho / \sqrt{K_{Ic}}$
Minimum cost	Stiffness	$C_m\rho / \sqrt[3]{E}$
Minimum cost	Strength	$C_m\rho / \sqrt{\sigma_y}$
Minimum cost	Toughness	$C_m\rho / \sqrt{K_{Ic}}$
Minimum energy	Stiffness	$H_m\rho / \sqrt[3]{E}$
Minimum energy	Strength	$H_m\rho / \sqrt{\sigma_y}$
Minimum energy	Toughness	$H_m\rho / \sqrt{K_{Ic}}$

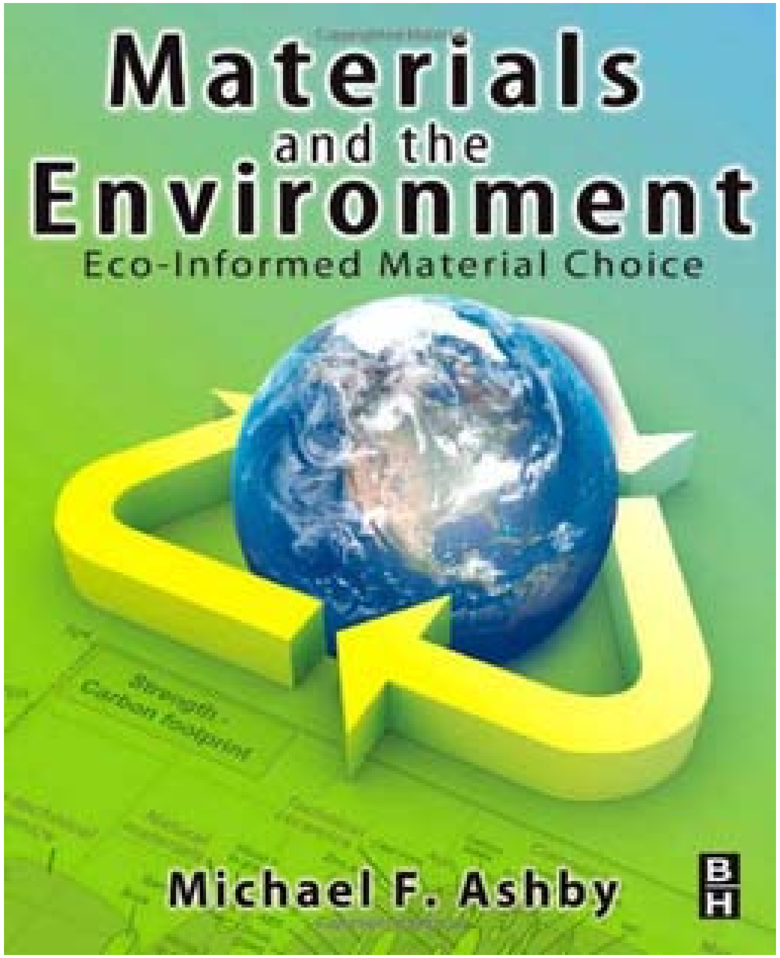
Penalty functions

$$Z = \prod_i M_i^{\alpha_i} \qquad Z = \sum_i \alpha_i \frac{M_i}{M_{i,\max}}$$

Name	Stage 1: Index	Stage 2: Index	Stage 3: Index	Mi/Mmax	Mi/Mmax	Mi/Mmax	SUM
Polyester/E-glass fiber, pultruded composite rod, unidirectional laminate	0,00171	0,00998	0,00265	1,00	1,00	1,00	**20,00**
Polyester/45wt% E-glass fiber, woven fabric composite, biaxial laminate	0,00162	0,00601	0,00207	0,95	0,60	0,78	**14,87**
Polyester/E-glass fiber, non-crimp fabric composite, quasi-isotropic laminate	0,00153	0,00557	0,00185	0,89	0,56	0,70	**13,57**
Aluminum, 7475, wrought, T651	0,00149	0,00443	0,00133	0,87	0,44	0,50	**10,74**
Aluminum, 7475, wrought, T7651	0,00149	0,00416	0,00136	0,87	0,42	0,51	**10,66**
Aluminum, 5182, wrought, H19	0,00155	0,00434	0,00126	0,91	0,43	0,48	**10,52**
Aluminum, 6010, wrought, T6	0,00152	0,00415	0,00125	0,89	0,42	0,47	**10,29**
Aluminum, 7475, wrought, T761	0,00148	0,00405	0,00122	0,87	0,41	0,46	**10,04**
max	0,00171	0,00998	0,00265	3	7	10	**weight factor**

TEXTBOOKS


Michael F. Ashby
Materials Selection in Mechanical Design
Fourth Edition
B H


Materials and the Environment
Eco-Informed Material Choice
Michael F. Ashby
B H

CES EDUPACK 2014 - GrantaDesign

http://www.grantadesign.com/education/edupack/edupack2014.htm