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Materials selection

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Lecture at
Jerusalem College of Engineering
Sami Shamoon College of Engineering Be’er Sheva

Content

- The Ashby approach for materials selection
- Translation phase
- Screening and ranking
- Search phase and final selection

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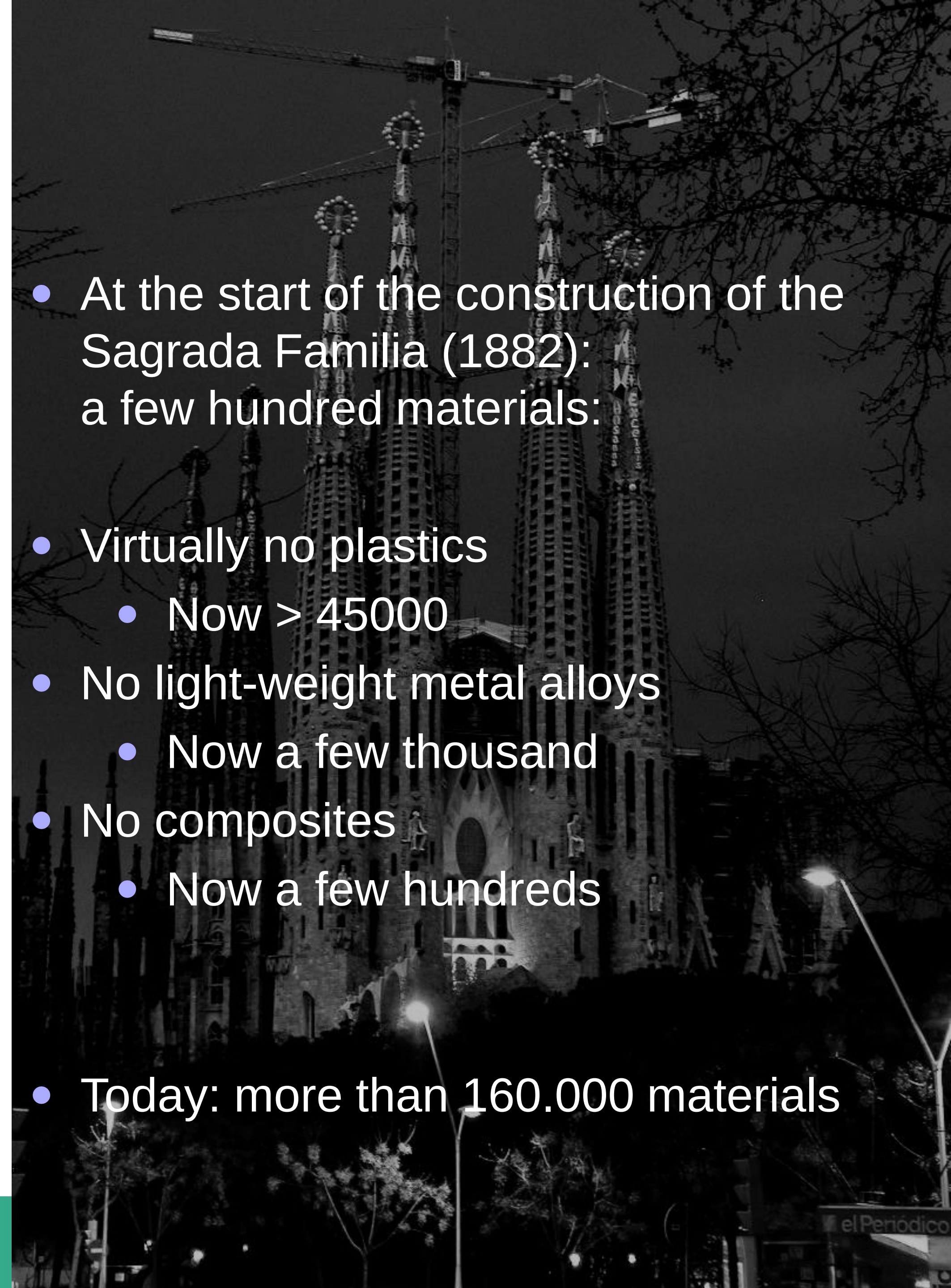
Justification

Antoni Gaudi



- At the start of the construction of the Sagrada Familia (1882):
  a few hundred materials:
- Virtually no plastics
  - Now > 45000
- No light-weight metal alloys
  - Now a few thousand
- No composites
  - Now a few hundreds
- Today: more than 160.000 materials

A CAR

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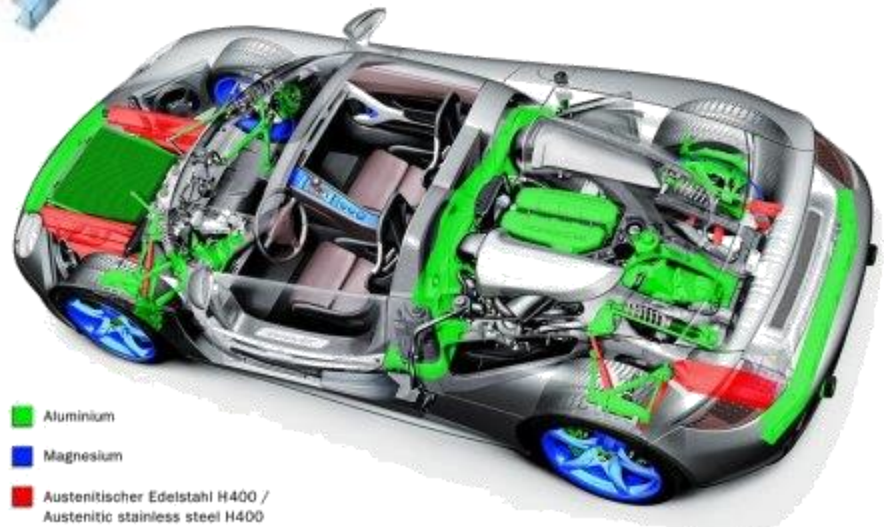
A light car



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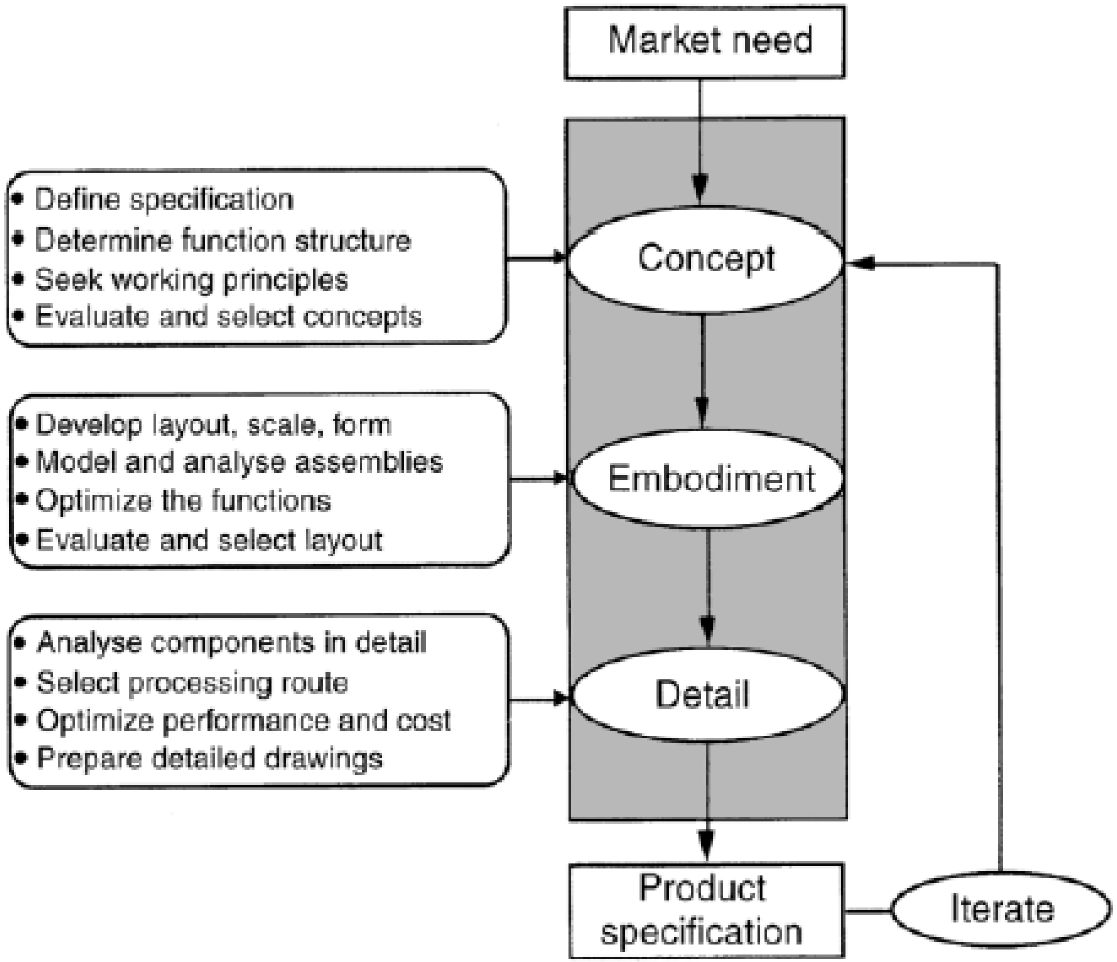
A cheap car

An environmentally friendly car

The design process



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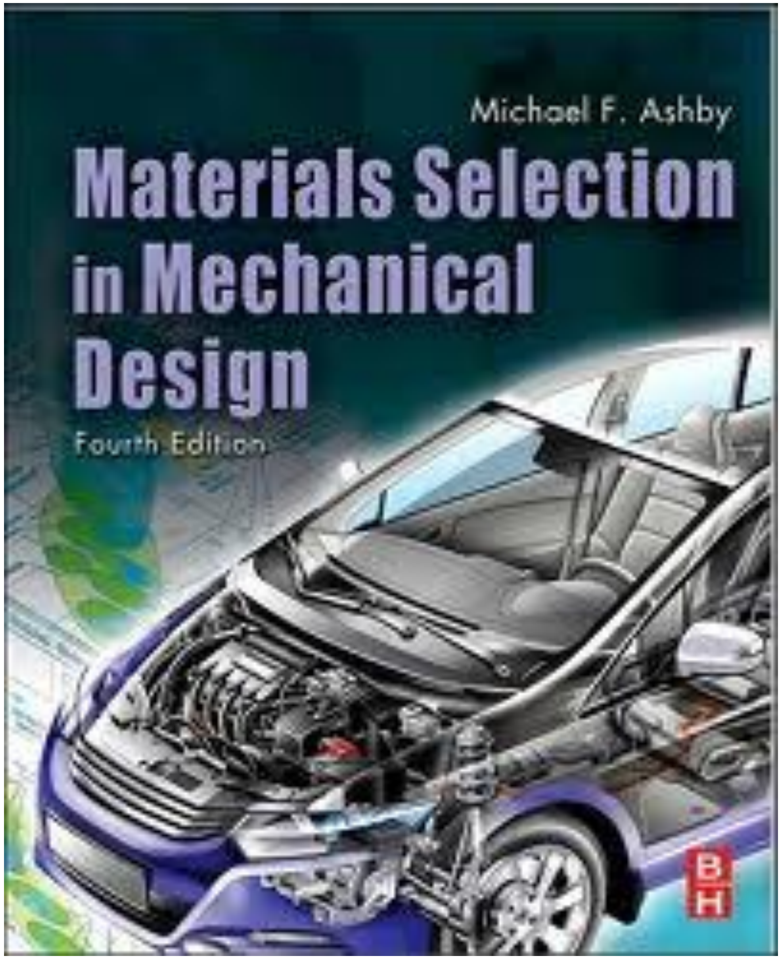
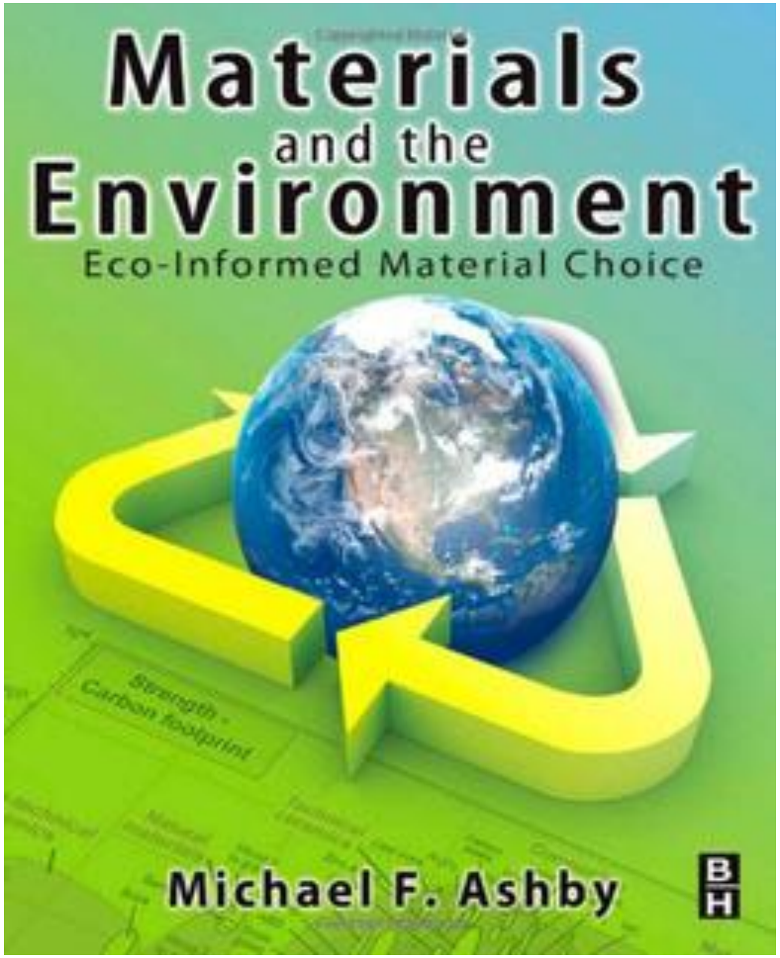
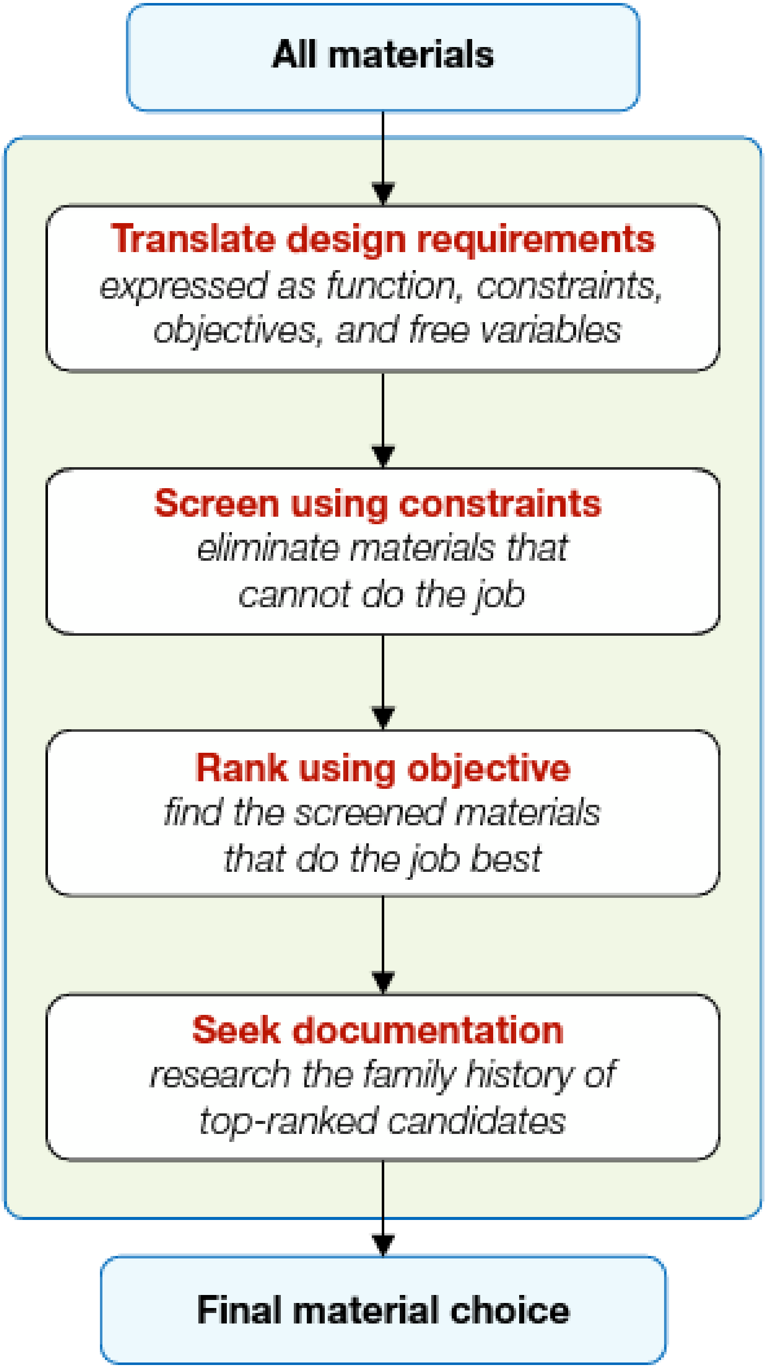
The Ashby approach

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

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

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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).

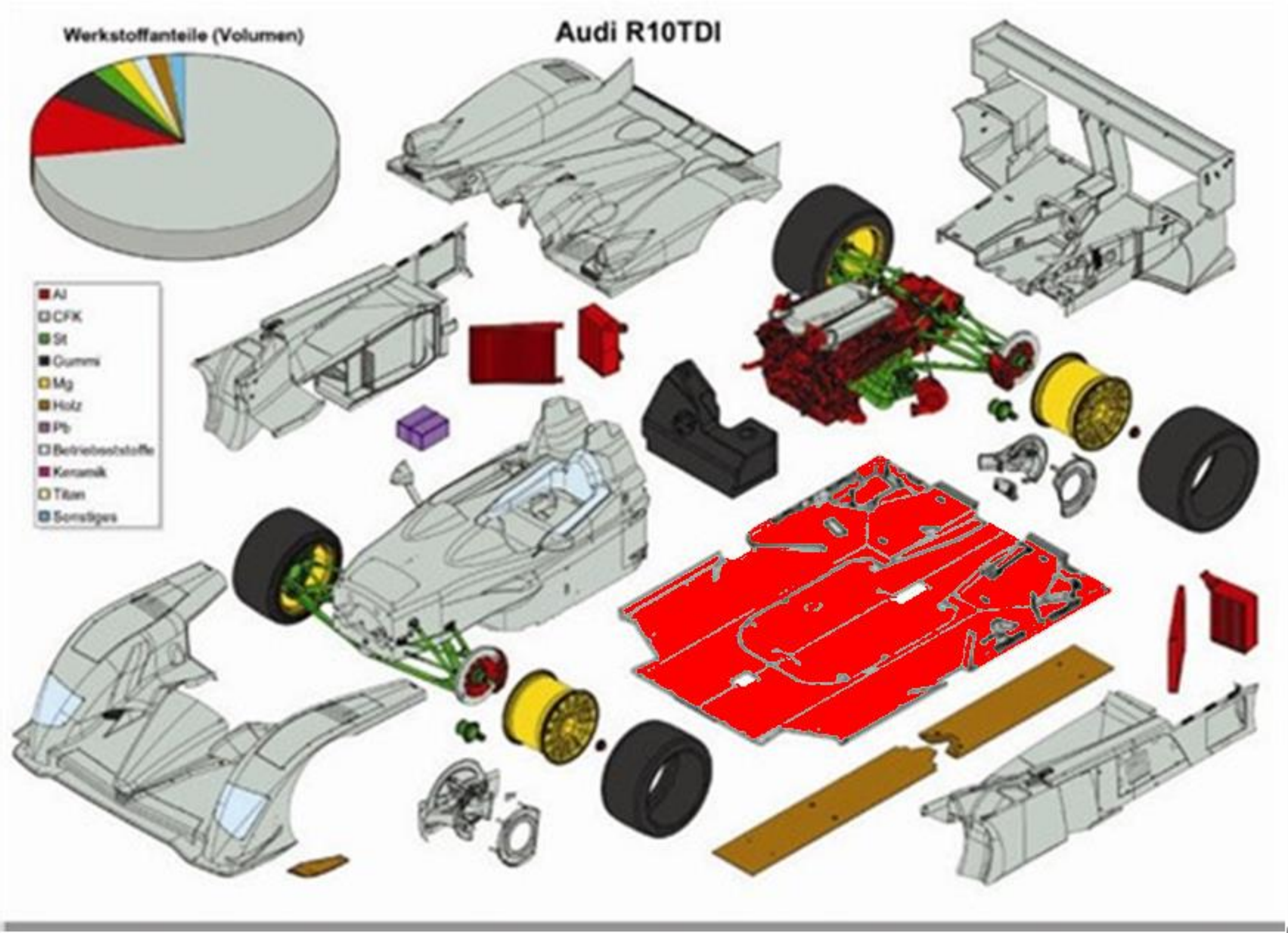
nonnegotiable conditions → screening

negotiable but desirable conditions → ranking

screening

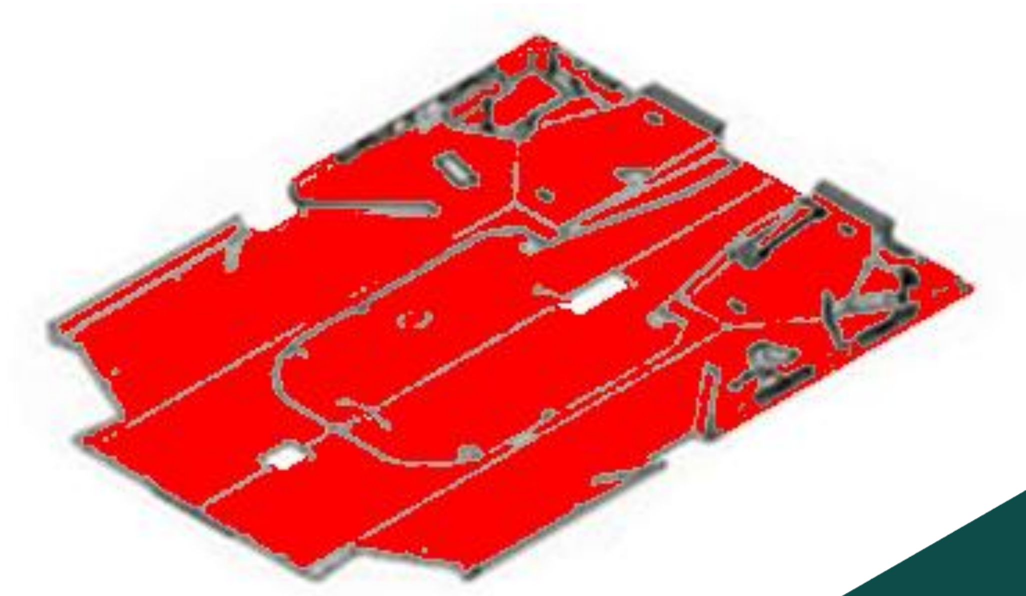
ranking

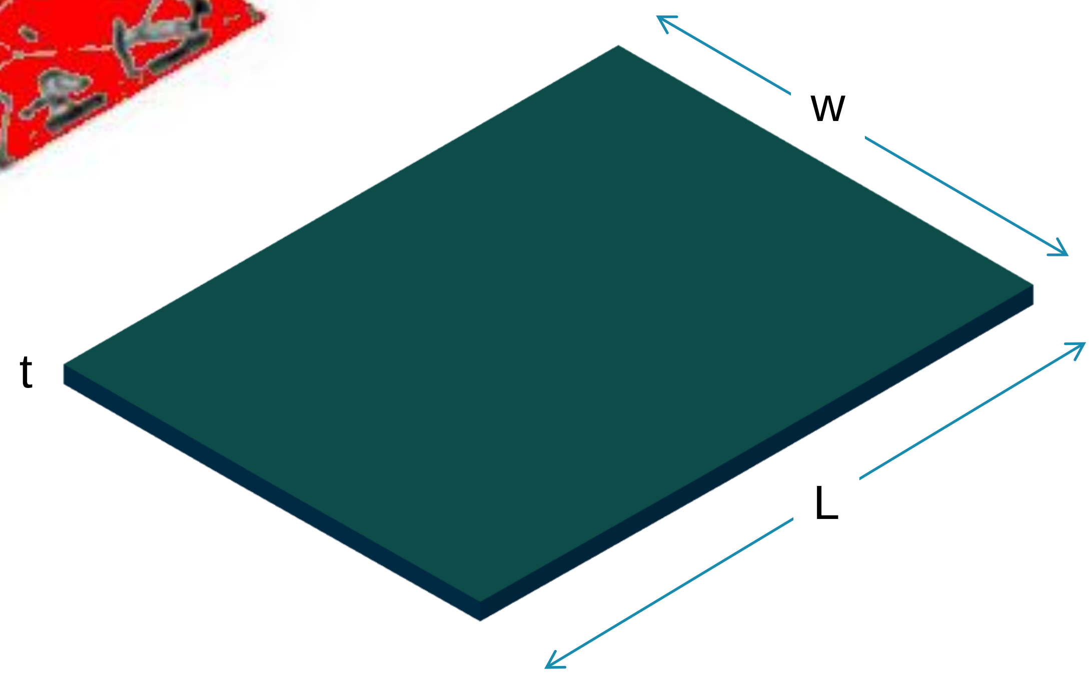
Our car: function



Objectives

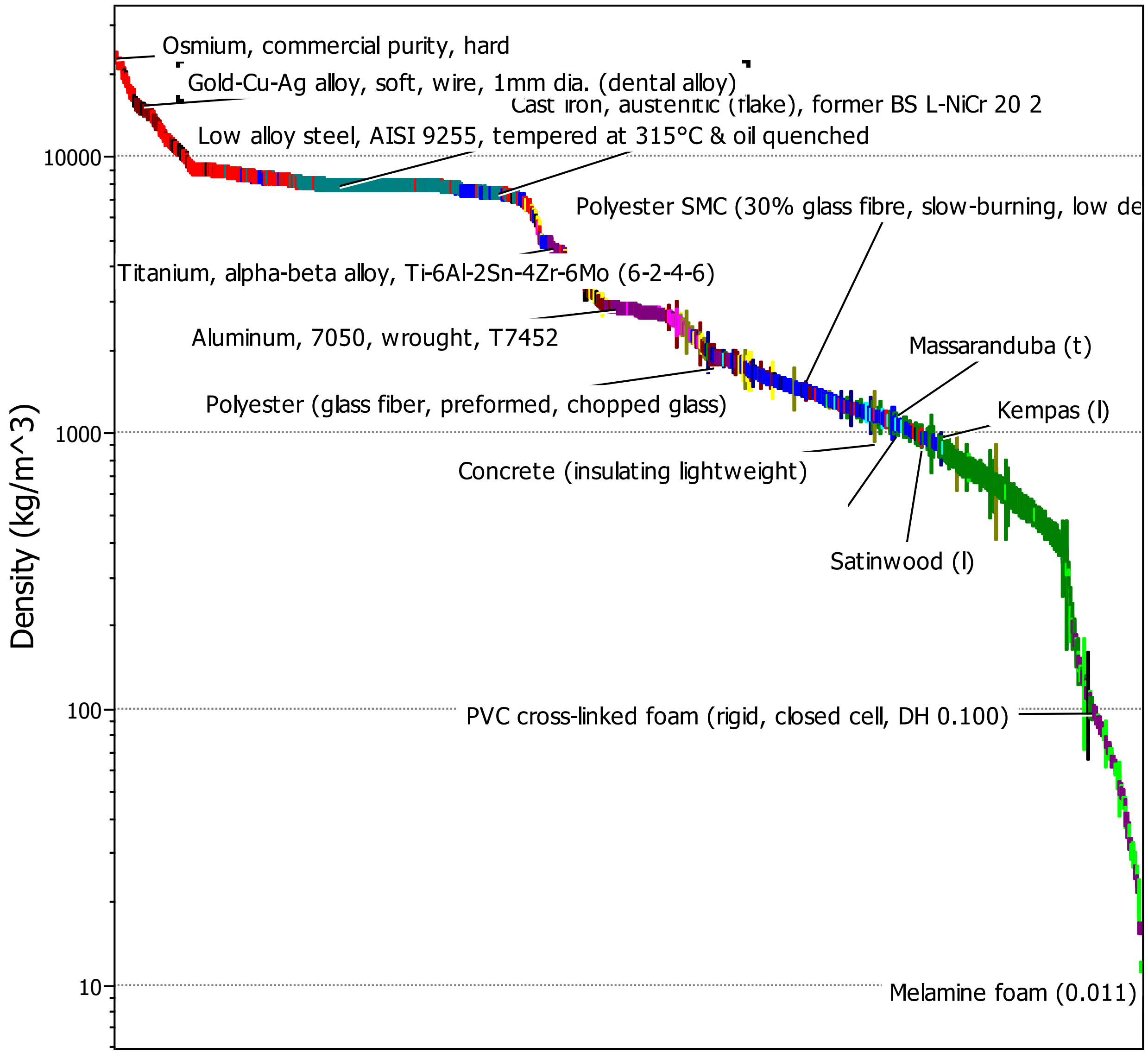
- Minimise weight/cost/environmental impact of bottom plate of car





An objective: minimize mass

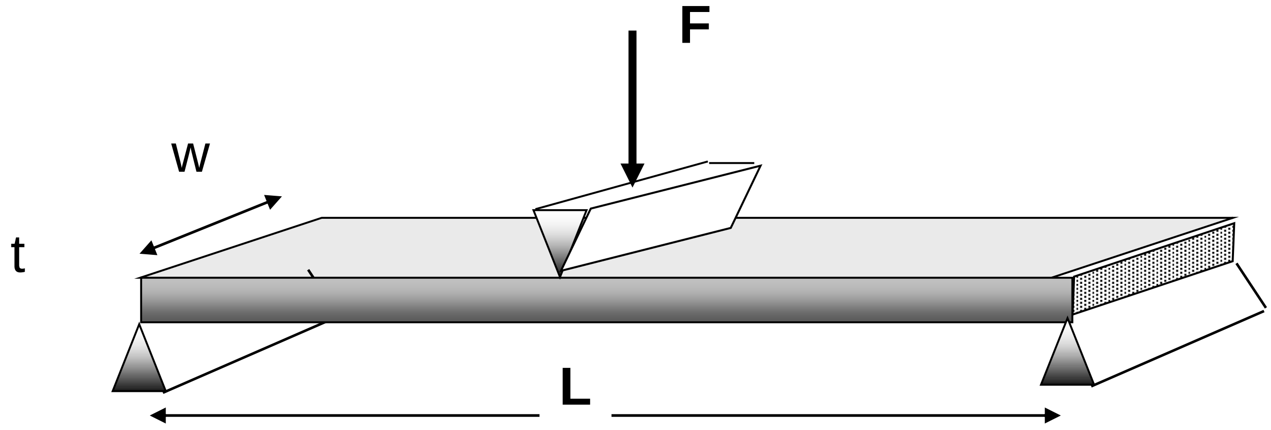
$$m = \rho \cdot L \cdot w \cdot t$$



Constraint 1

=> Limited elastic deformation

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



Translation

Table 5.1 Function, Constraints, Objectives, and Free Variables

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**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).*

Free variable(s)

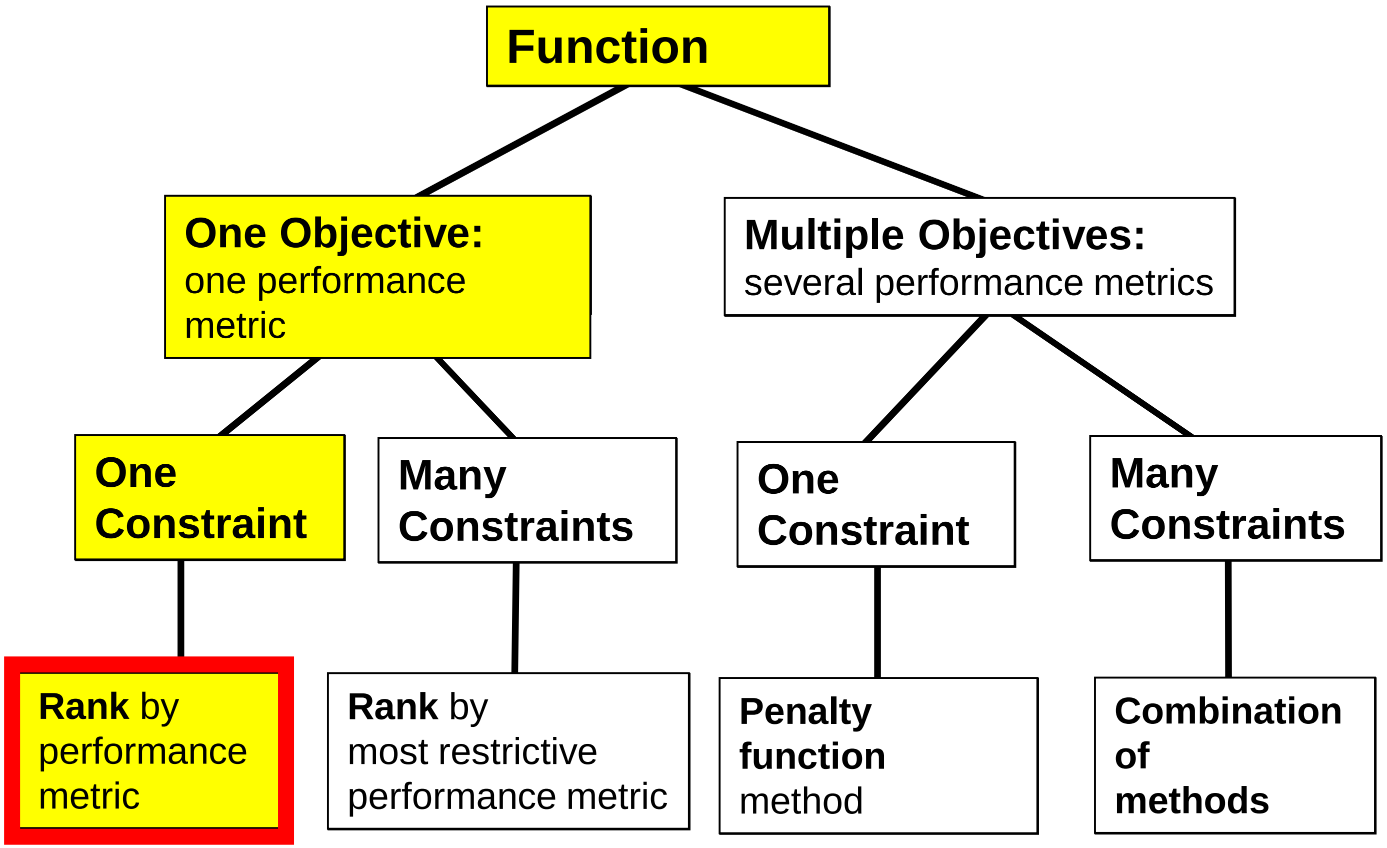
- L & w are determined by car dimensions
- => **constants**

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

Simplest case

Simplest case:

Design with one objective, meeting a single constraint



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**

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

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

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

Load

Geometry

Material Properties

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Material Index MI

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

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

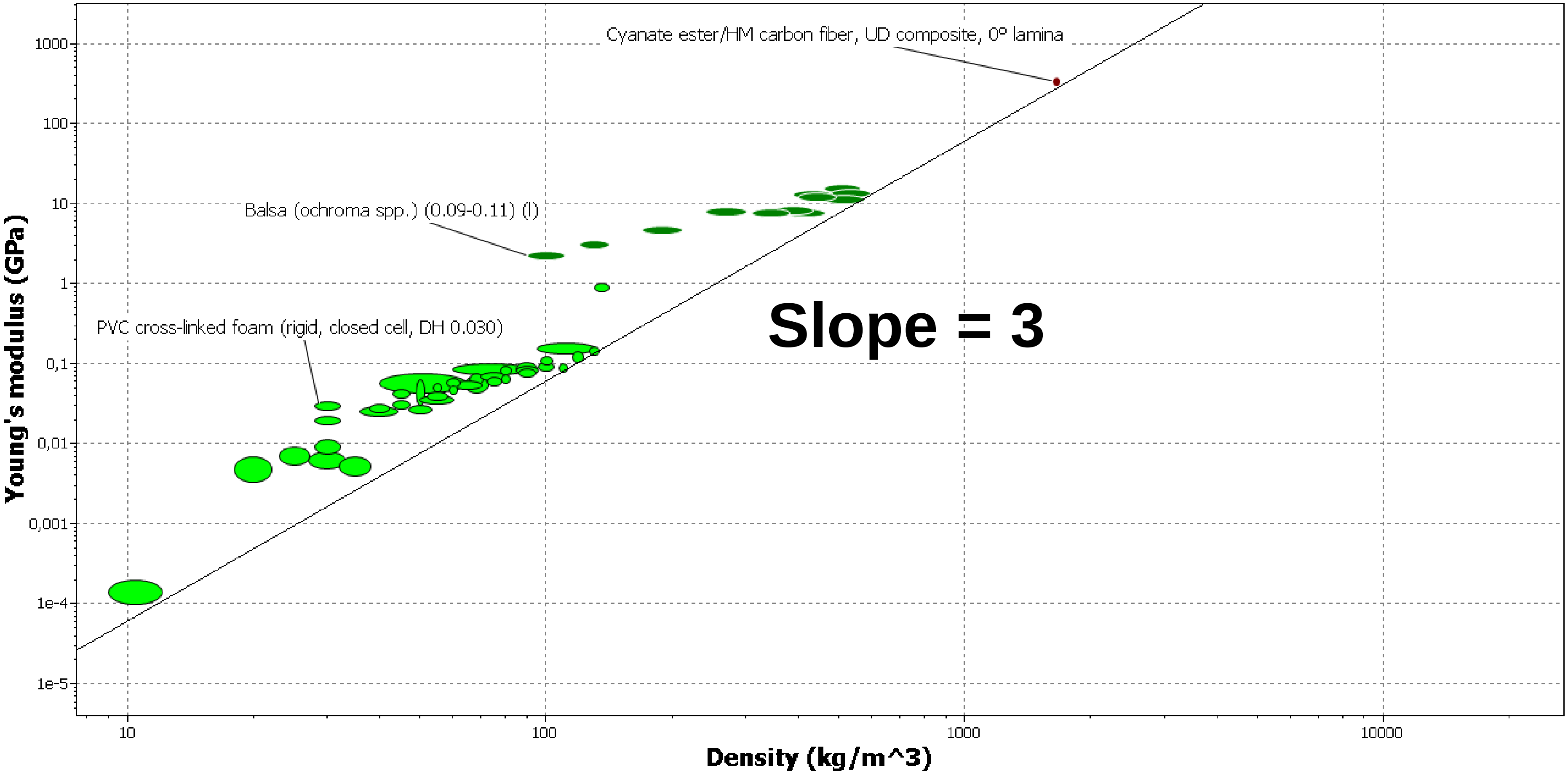
Log(E)-3log(ρ) = 3log(MI')

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!

The foam car

Size to achieve the needed mechanical performance?

How to insert hinges, etc?

Fire resistance?

The wooden car

Corrosion Properties ?

Screening

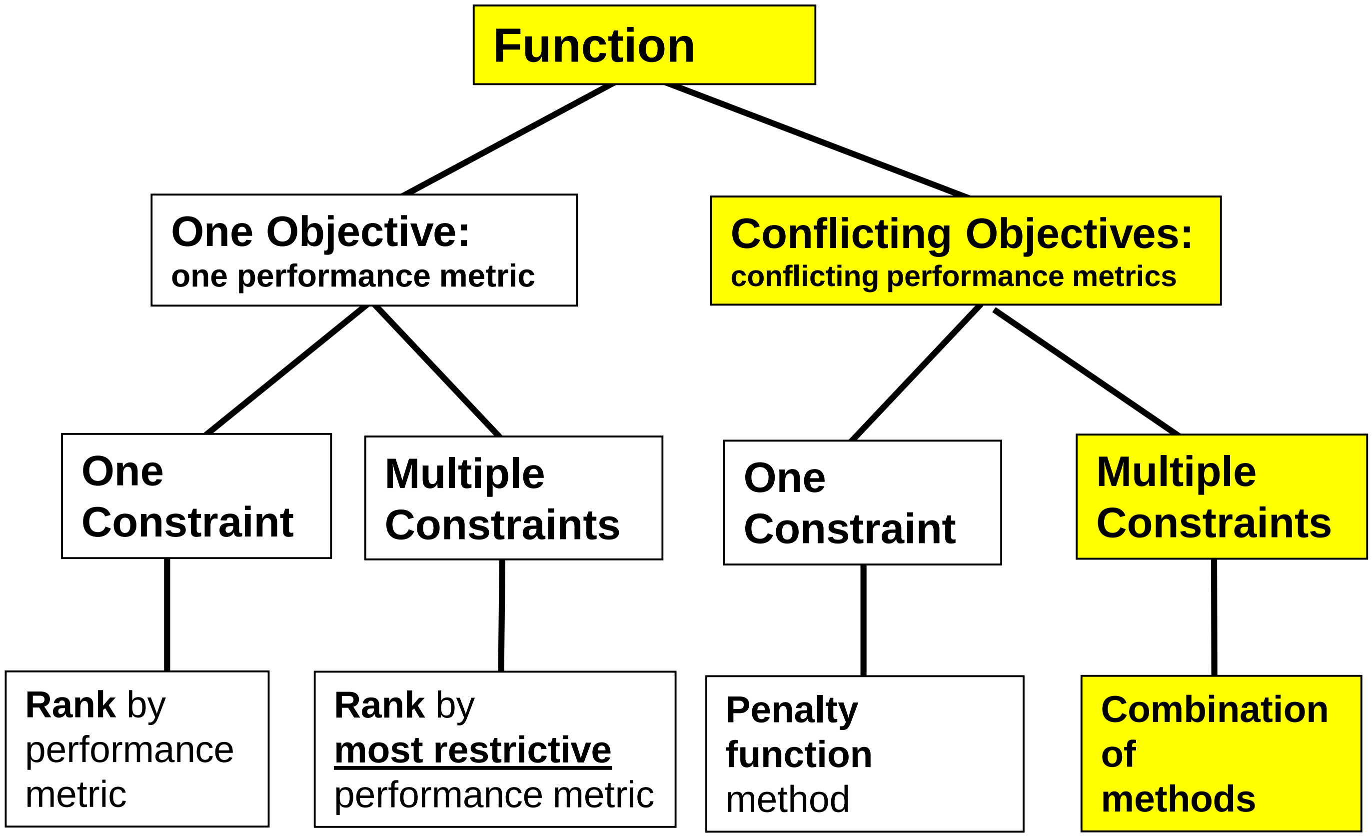
Working of wood

Shaping possibilities?

Check afterwards

Check production costs

The ultimate challenge



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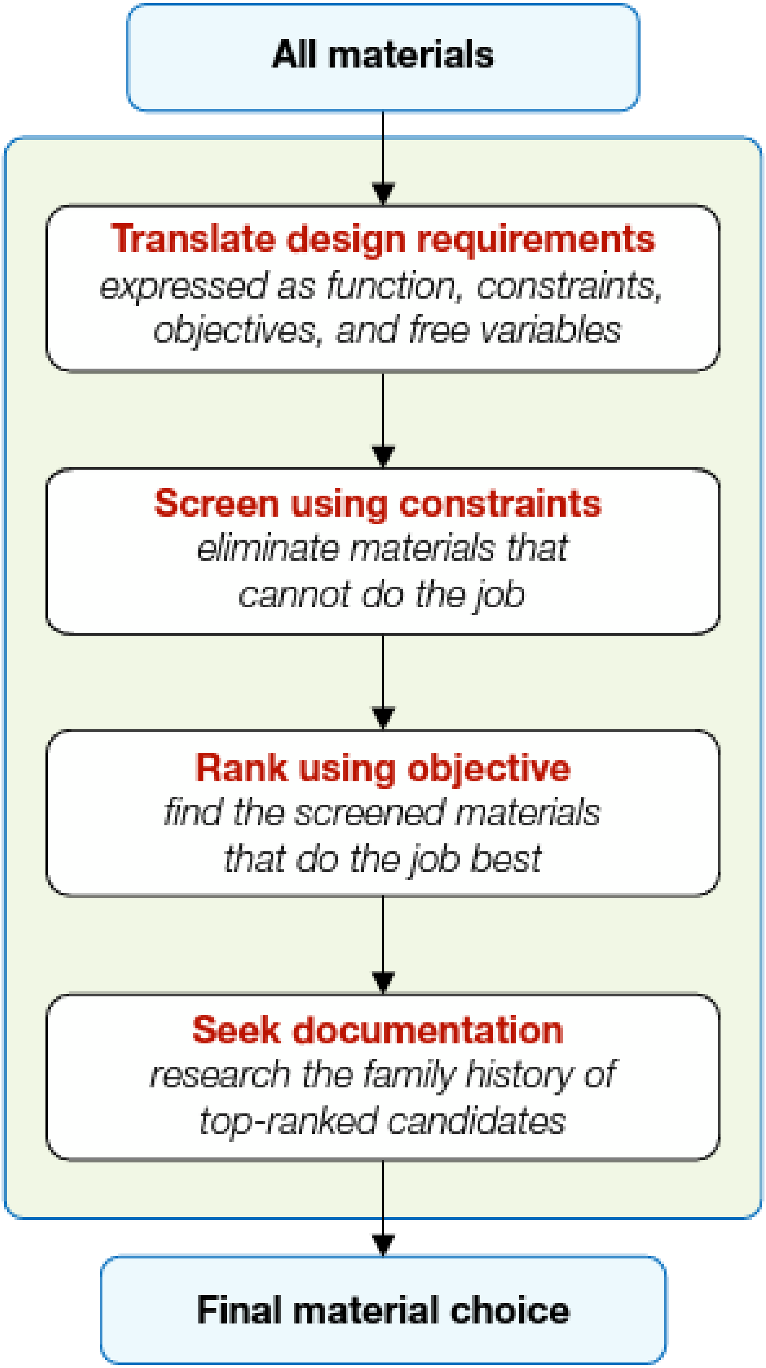
The case

The topic

- CO_2-cartridge
- Applications:
  - Pressure source in paintball gu
  - Emergency kit to inflate tires
  - Life jackets
- Economics
  - Small size (70 mm length)
  - Mass production
  - No re-use, but recycling

Steps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translation

Brainstorm
Function
Objectives
Free variable
Constraints
non-negotiable (➔ screening)
negotiable (➔ ranking)

Brainstorm on the cartridge

- Withstand internal pressure in a safe way (typical 9 bar)
- Yield before break
- Corrosion resistant
- UV resistant
- Low cost
- Resistant to thermal shock
- Minimal weight
- Water proof
- Minimal ecological impact
- Limited thermal conductivity
- Function within -25 to +60°C temperature range
- Mass production possible

CO_2-cartridge: function

- Function: must contain gas
- Shape: cylinder, volume defined by length L and radius R
- Objectives:
  - Minimal weight $m = \rho 2\pi RtL$
  - Minimal cost $C = C_m \rho 2\pi RtL$
  - Minimal energy for production $H = H_m \rho 2\pi RtL$

- Free variable: wall thickness t

Screening or ranking?

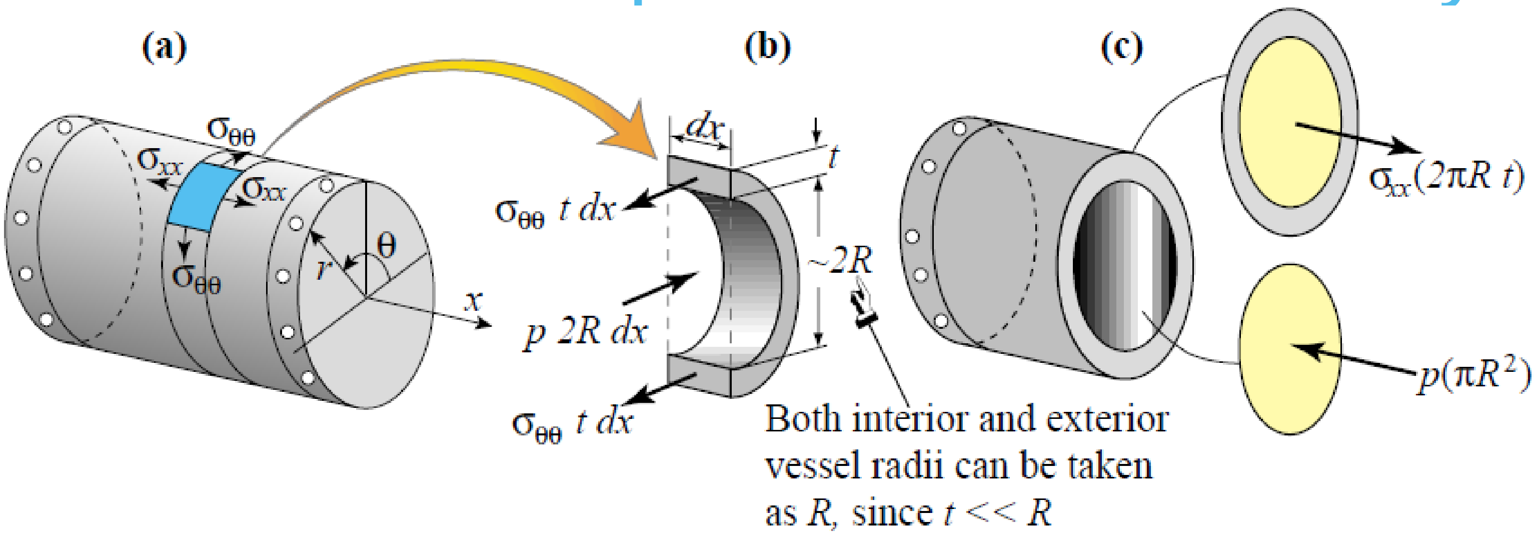
- Withstand internal pressure in a safe way
- Yield before break
- Corrosion resistant
- UV resistant
- Resistant to thermal shock
- Water proof
- Limited deformation under pressure
- Function within -25 to +60°C temperature range
- Mass production possible
- Cylindrical shape

SCREENING

PROCESS

SHAPE

Withstand internal pressure in a safe way



- End effects neglected
- Thin walled vessel $\sigma_{\theta\theta} = \dfrac{pR}{t}$ $\sigma_{xx} = \dfrac{pR}{2t}$
- Withstanding pressure = not exceed yield strength:

$$\sigma_{\theta\theta} = \frac{pR}{t} \leq \sigma_y$$

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Yield before break

- Avoid brittle failure $K_{Ic} > K_I = Y\sigma\sqrt{\pi a}$

- Yield before break means:

$$K_{Ic} > K_I = Y\sigma_y\sqrt{\pi a}$$

Thermal shock

- Expansion of the gas = sudden temperature drop
  Filling of the tank = significant temperature increase

- Expansion of the material $\Delta L = L_0 \alpha \Delta T \Rightarrow \varepsilon_{th} = \alpha \Delta T$

- This expansion forces surrounding material to deform as well, and this builds up stress:

$$\sigma = E\varepsilon_{th} = E\alpha\Delta T < \sigma_y$$

Limited deformation under pressure

- Deformation of the container must be limited to ΔR_{max}

$$\Delta R_{\max} > \Delta R = \varepsilon R = \frac{\sigma}{E} R = \frac{pR^2}{Et}$$

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Screening

Material screening parameters

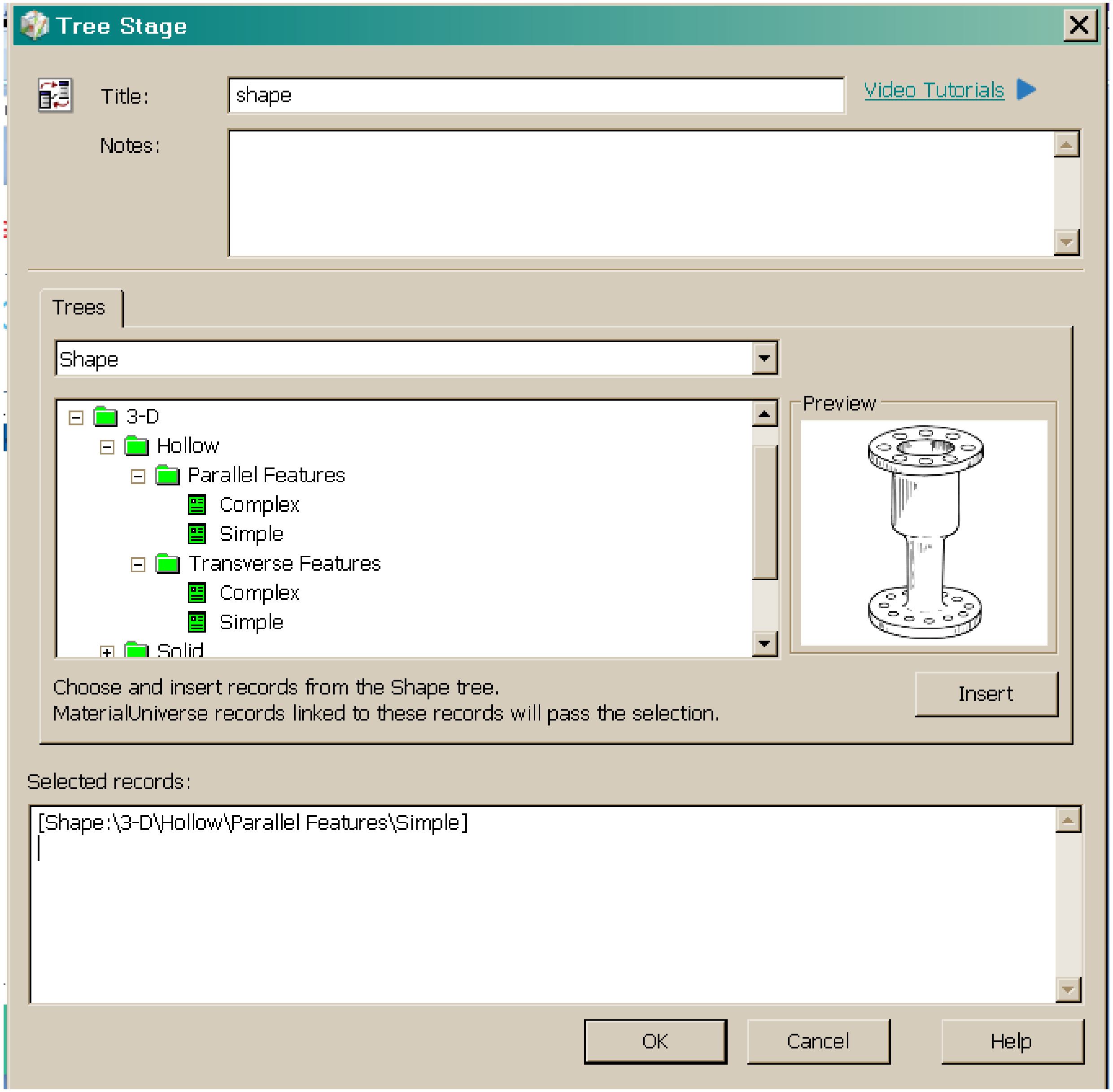
Corrosion resistant

UV resistant

Water proof

▾ Durability	
Water (fresh)	Acceptable; Excellent
Water (salt)	Limited use; Acceptable; Excellent
Weak acids	Limited use; Acceptable; Excellent
Strong acids	
Weak alkalis	Limited use; Acceptable; Excellent
Strong alkalis	
Organic solvents	Limited use; Acceptable; Excellent
Oxidation at 500C	
UV radiation (sunlight)	Good; Excellent
Flammability	

Shape


Tree Stage
Title:
shape
Video Tutorials
Notes:
Trees
Shape
3-D
Hollow
Parallel Features
Complex
Simple
Transverse Features
Complex
Simple
Solid
Preview
Choose and insert records from the Shape tree.
MaterialUniverse records linked to these records will pass the selection.
Insert
Selected records:
[Shape:\3-D\Hollow\Parallel Features\Simple]
OK
Cancel
Help

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Ranking

Withstand internal pressure in a safe way

- Constraint:

$$\sigma_{\theta\theta} = \frac{pR}{t} \le \sigma_y \qquad t = \frac{pR}{\sigma_y}$$

- Objectives
  - Minimal mass

    $$m = \rho 2\pi R t L$$

    $$m = \rho R L \frac{pR}{\sigma_y} = 2\pi \cdot p \cdot R^2 L \left[\frac{\rho}{\sigma_y}\right]$$ **MI1**

  - Minimal cost

    $$C = C_m \rho 2\pi R t L$$

    $$C = 2\pi \cdot p \cdot R^2 L \left[\frac{\rho C_m}{\sigma_y}\right]$$ **MI2**

  - Minimal embodied energy

    $$H = H_m \rho 2\pi R t L$$

    $$H = 2\pi \cdot p \cdot R^2 L \left[\frac{\rho H_m}{\sigma_y}\right]$$ **MI3**

Yield before break

- Yield before break means:

$$K_{Ic} > K_I = Y\sigma_y\sqrt{\pi a}$$

- Only one free variable
- Safest design tolerates the largest defect:

$$a = \frac{1}{Y^2\pi}\left(\frac{K_{Ic}}{\sigma_y}\right)^2 \quad \textbf{MI4}$$

Thermal shock

- This expansion forces surrounding material to deform as well, and this builds up stress:

$$\sigma = E\varepsilon_{th} = E\alpha\Delta T < \sigma_y$$

- Only one free variable
- Best material is the one that allows the biggest temperature difference

$$\Delta T = \frac{\sigma_y}{E\alpha}$$

MI5

Limited deformation under pressure

- Deformation of the container must be limited to Δrmax

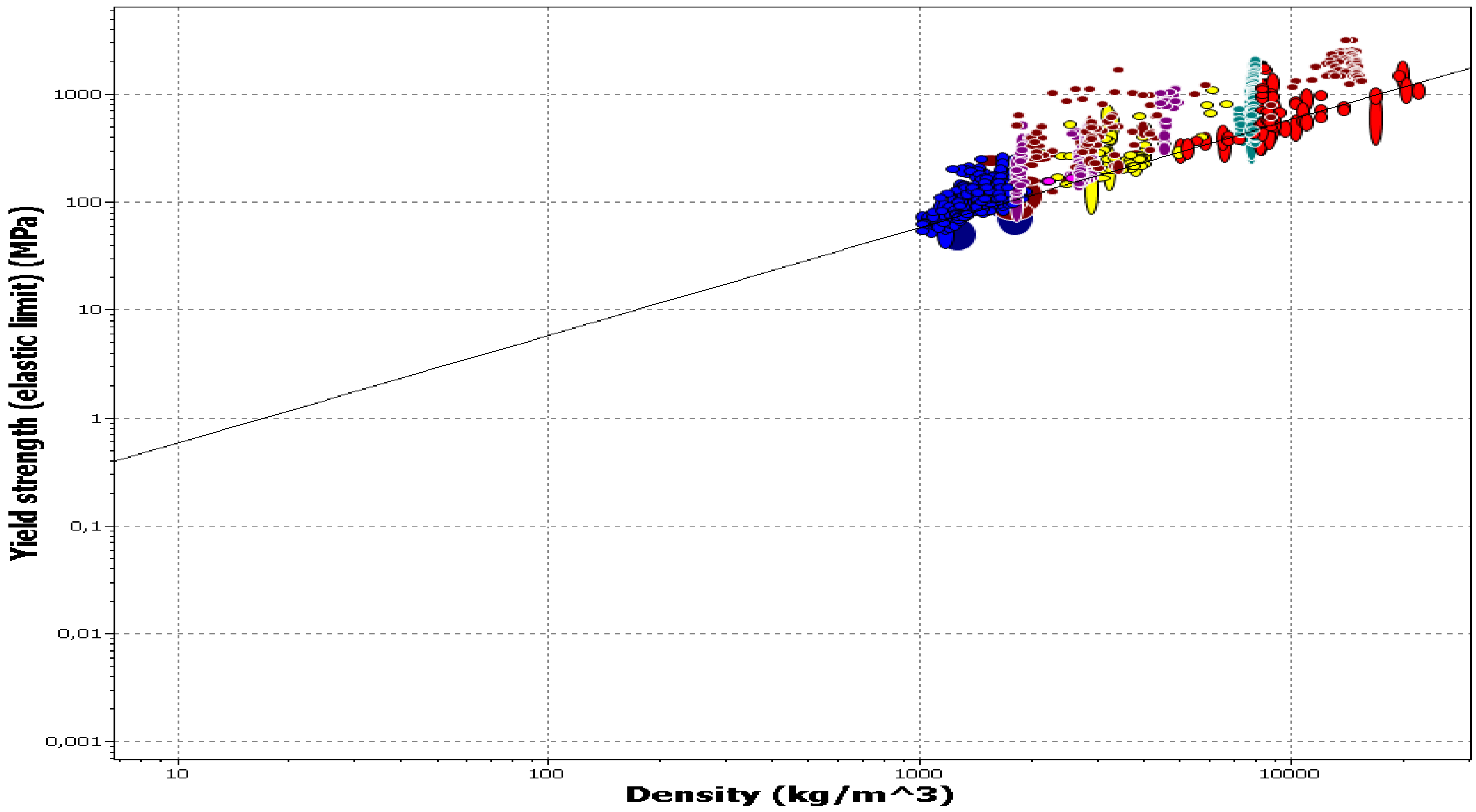
$$\Delta R_{\max} > \Delta R = \varepsilon R = \frac{\sigma}{E} R = \frac{pR^2}{Et} \qquad t = \frac{pR^2}{E\Delta R}$$

- Objectives
  - Minimum mass
    $$m = \rho 2\pi RtL \qquad m = \rho 2\pi RL \frac{pR^2}{E\Delta R} = 2\pi \cdot p \cdot \frac{R^3 L}{\Delta R}\left[\frac{\rho}{E}\right]$$ **MI6**
  - Minimum cost
    $$C = C_m \rho 2\pi RtL \qquad C = 2\pi \cdot p \cdot \frac{R^3 L}{\Delta R}\left[\frac{C_m \rho}{E}\right]$$ **MI7**
  - Minimum embodied energy
    $$H = H_m \rho 2\pi RtL \qquad H = 2\pi \cdot p \cdot \frac{R^3 L}{\Delta R}\left[\frac{H_m \rho}{E}\right]$$ **MI8**

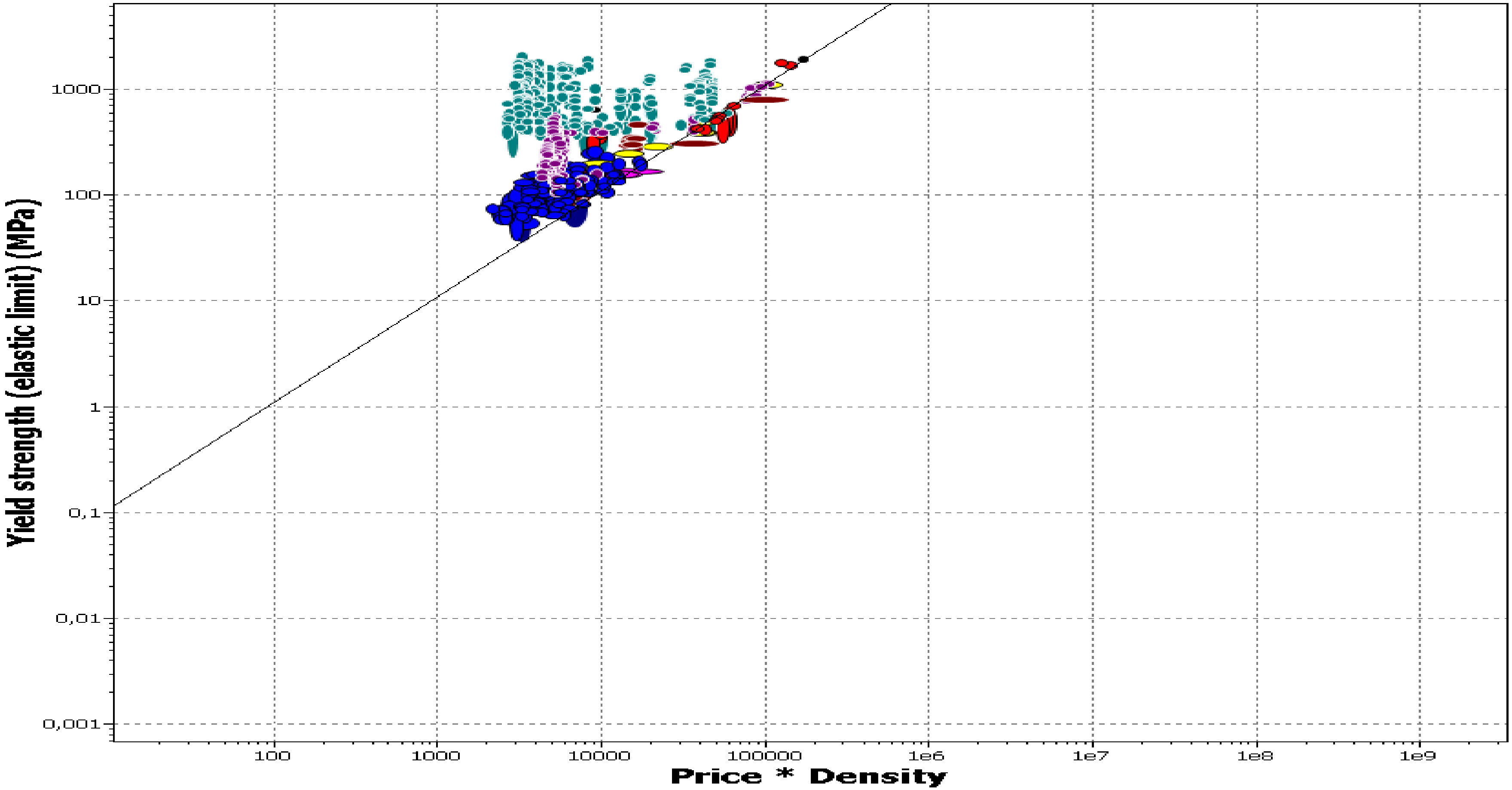
Overview

MI	Objective	MI	Max/min	X	Y	slope
1	Mass	σ_y / ρ	Max	ρ	σ_y	1
2	Cost	$\sigma_y / C_m\rho$	Max	$C_m\rho$	σ_y	1
3	Energy	$\sigma_y / H_m\rho$	Max	$H_m\rho$	σ_y	1
4	-	K_{Ic} / σ_y	Max	σ_y	K_{Ic}	1
5	-	$\sigma_y / E\alpha$	Max	$E\alpha$	σ_y	1
6	Mass	E / ρ	Max	ρ	E	1
7	Cost	$E / C_m\rho$	Max	$C_m\rho$	E	1
8	Energy	$E / H_m\rho$	Max	$H_m\rho$	E	1

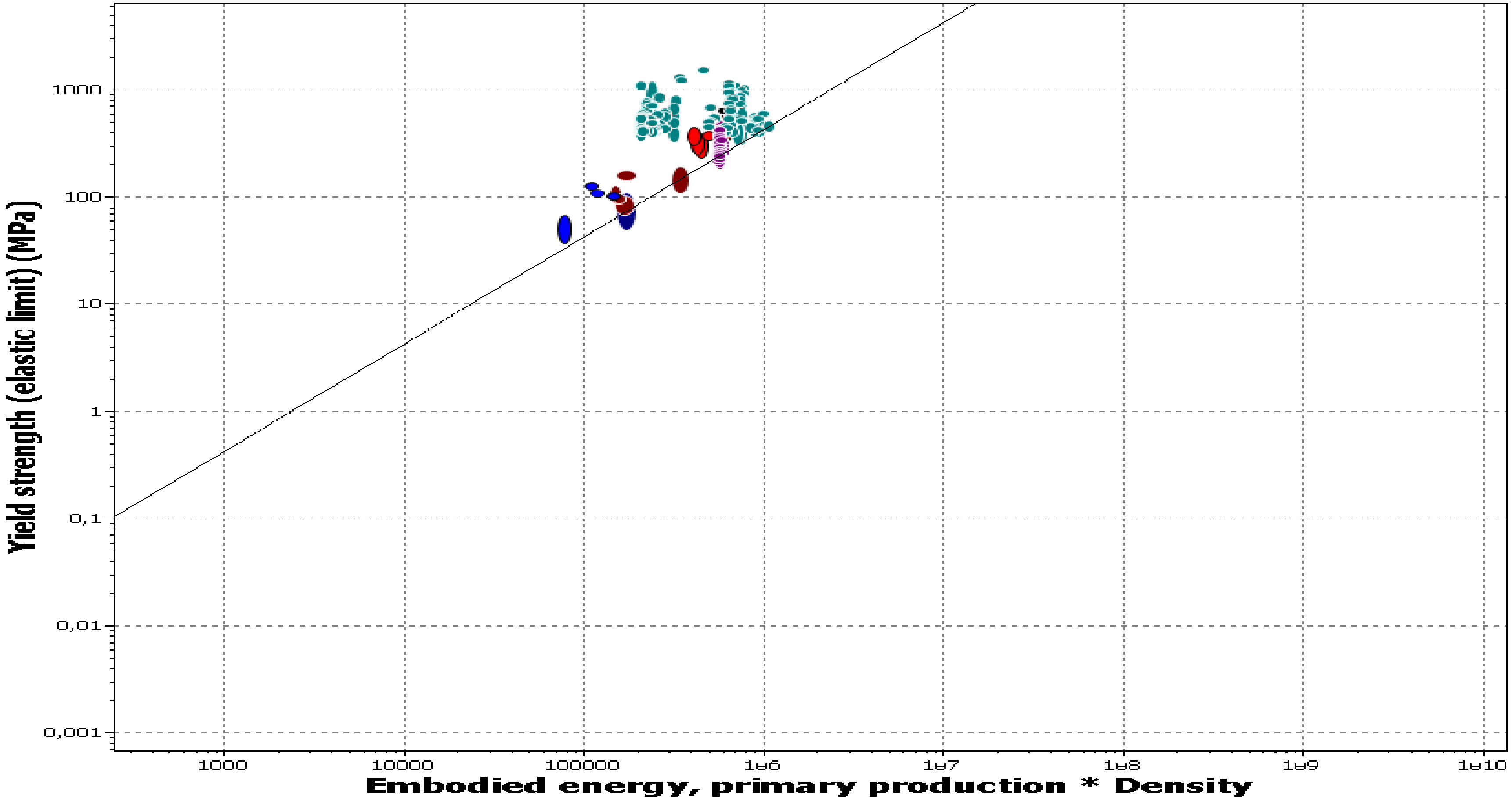
MI1: yield / mass



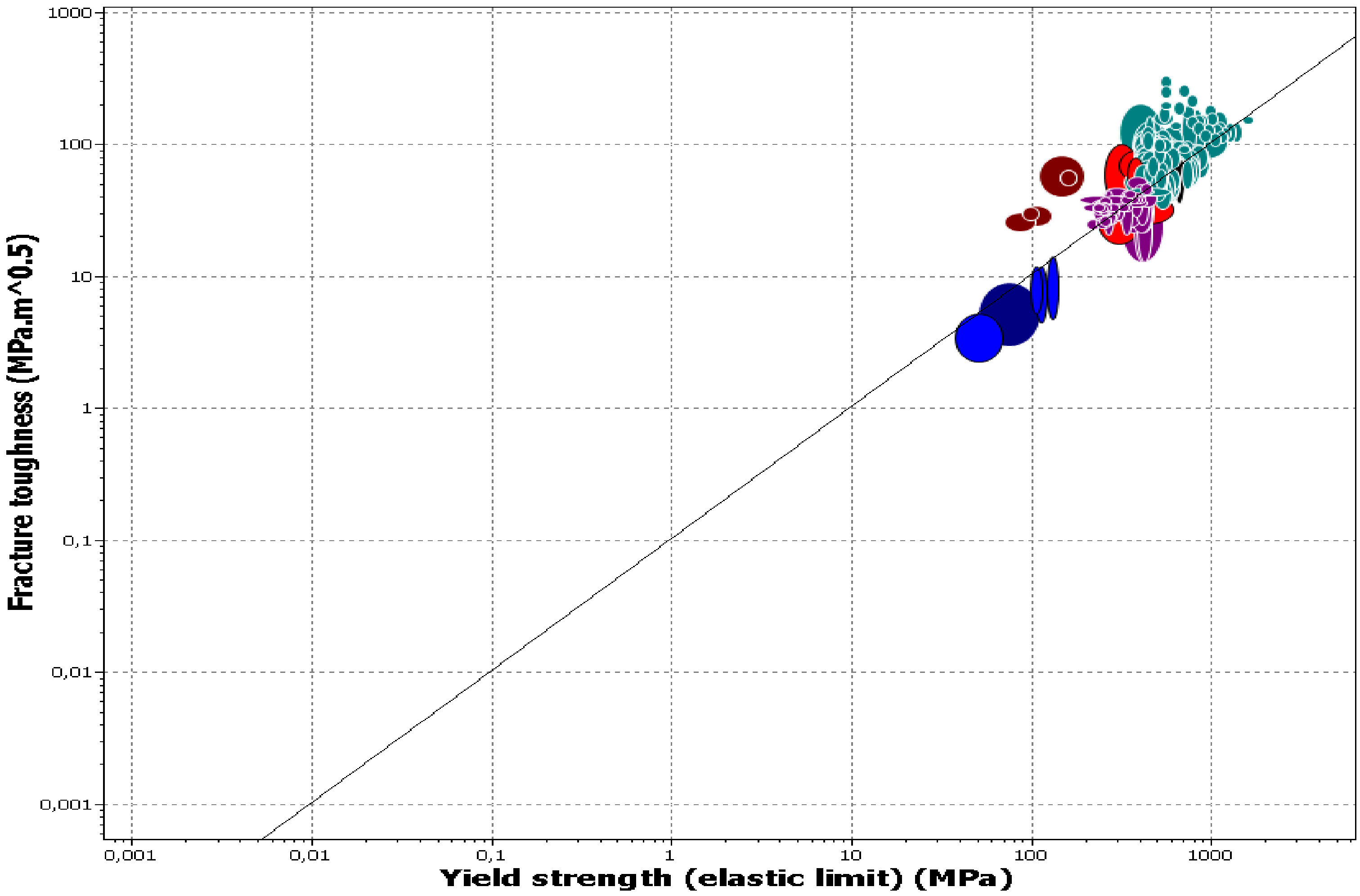
MI2: yield / cost



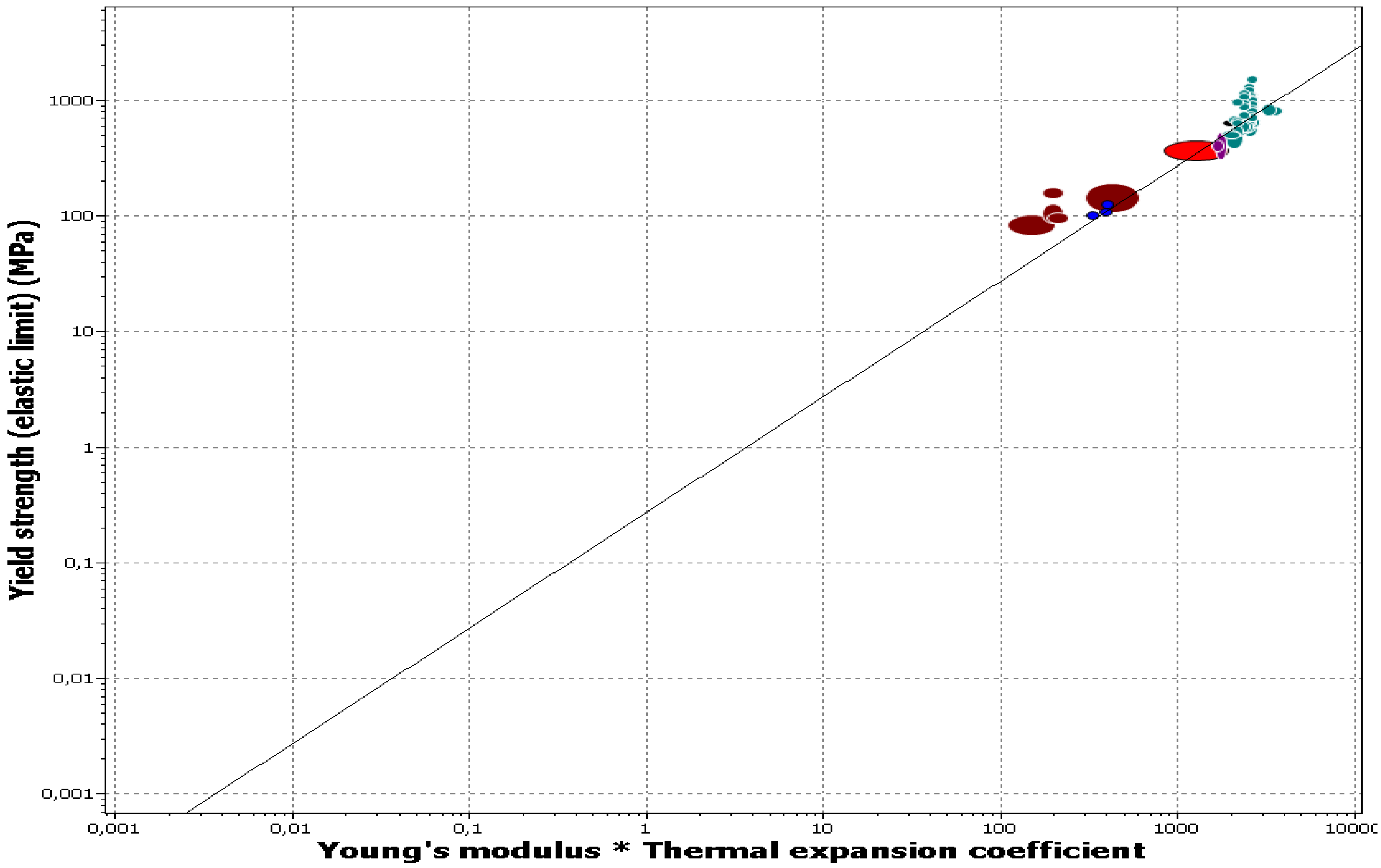
MI3: yield / embodied energy



MI4: yield before break



MI5: thermal shock

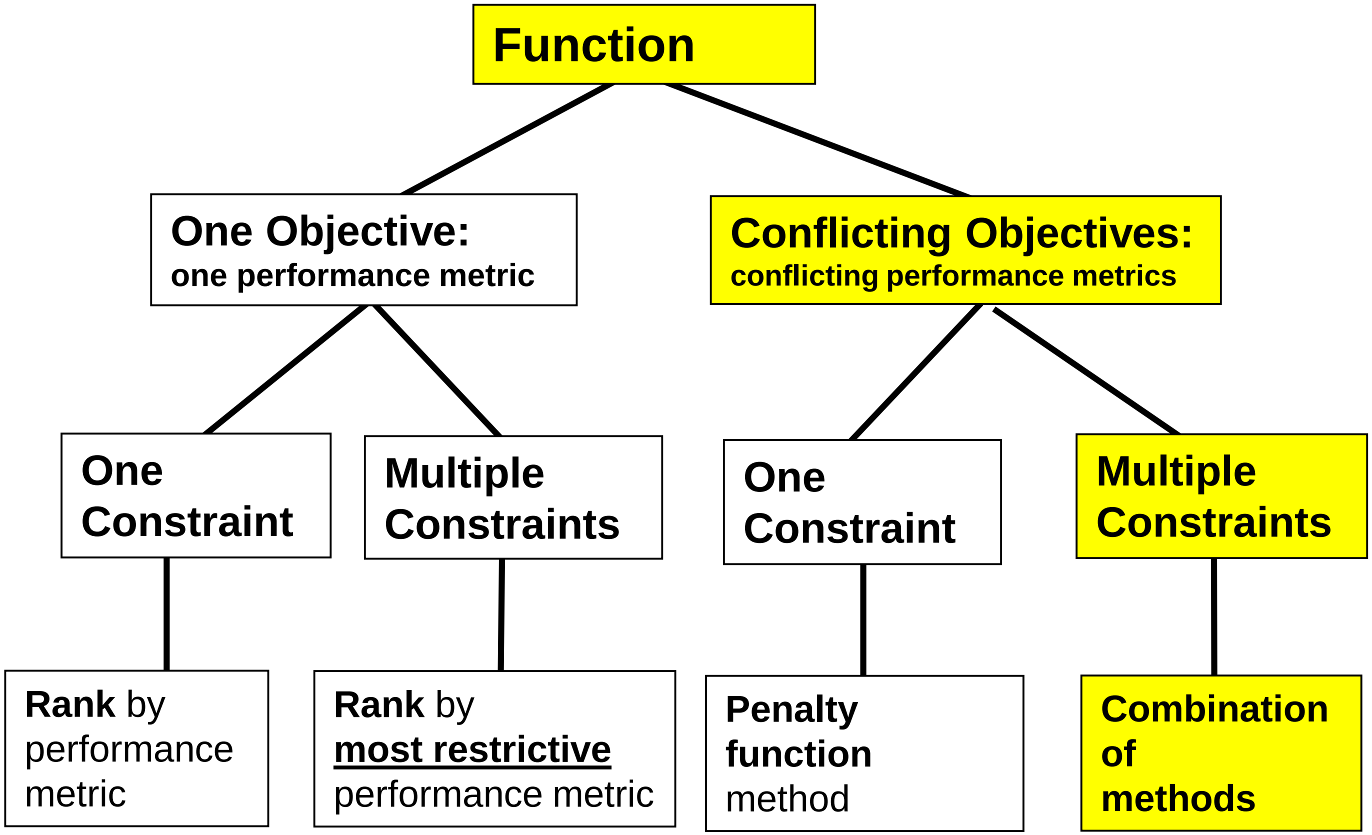


Results

- 58 materials pass all criteria
  - Al 7075
  - Steel
    - Carbon steel
    - Complex phase steel
    - Low alloy steel
    - Stainless steel

- Further refining : 14 steel alloys

How to get the best?



$$Z = \prod_i M_i^{\alpha_i}$$

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

Overview of top ranking materials (α_i=1)

Name	1	2	3	4	5	6	7	8	product
Complex phase steel, YS800 (cold rolled)	0,101	0,149	0,0025	0,105	0,316	0,0268	0,0395	6,54E-04	8,54
Low alloy steel, AISI 4135, air melted, quenched & tempered	0,117	0,26	0,0039	0,114	0,35	0,0262	0,0583	8,80E-04	64,12
Press hardening steel, 22MnB5, austenized & H20 quenched, coated	0,139	0,38	0,0053	0,134	0,436	0,0268	0,073	0,00101	322,57
Press hardening steel, 22MnB5, austenized & H20 quenched, uncoated	0,139	0,38	0,0053	0,134	0,436	0,0268	0,073	0,00101	322,57
Stainless steel, martensitic, 15-5PH, wrought, H1075	0,116	0,0193	0,0012	0,13	0,386	0,0258	0,0043	2,76E-04	0,04
Stainless steel, martensitic, 17-4PH, cast, H1000	0,12	0,0202	0,0012	0,136	0,364	0,0258	0,0043	2,64E-04	0,04
Stainless steel, martensitic, 17-4PH, cast, H1100	0,111	0,0252	0,0013	0,175	0,336	0,0257	0,0059	3,04E-04	0,10
Stainless steel, martensitic, 17-4PH, wrought, H1025	0,134	0,0225	0,0014	0,122	0,406	0,0258	0,0043	2,64E-04	0,06
Stainless steel, martensitic, 17-4PH, wrought, H1075	0,118	0,0197	0,0012	0,155	0,393	0,0258	0,0043	2,64E-04	0,05
Stainless steel, martensitic, AISI 420F, wrought	0,0889	0,109	0,0014	0,136	0,335	0,0258	0,0316	4,05E-04	2,04
Stainless steel, martensitic, Custom 450, wrought, H1000	0,14	0,0279	0,0017	0,123	0,47	0,0265	0,0053	3,28E-04	0,18
Stainless steel, martensitic, Custom 450, wrought, H1050	0,124	0,0248	0,0015	0,187	0,417	0,0265	0,0053	3,28E-04	0,17
Stainless steel, martensitic, Custom 450, wrought, H1100	0,0982	0,0195	0,0012	0,285	0,329	0,0265	0,0053	3,28E-04	0,10
Stainless steel, martensitic, PH 13-8Mo, wrought, H1100	0,127	0,0226	0,0015	0,161	0,457	0,0259	0,0046	3,13E-04	0,12

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Search

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Adding importance to MI's

- Mass, weight, energy: No effect on top 3
  1. Press hardening steel, 22MnB5, austenized & H20 quenched, uncoated
  2. Press hardening steel, 22MnB5, austenized & H20 quenched, uncoated
  3. Low alloy steel, AISI 4135, air melted, quenched & tempered

Steel 22MnB5

- Cold-rolled boron steel 22MnB5 is a high-strength steel product with good formability. Suitable for products requiring formability in delivery condition and high strength as a final product, the steel’s strength and hardness are achieved by quench hardening after forming.

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What if no coatings are to be used

- Martensitic stainless steel

Name	1	2	3	4	5	6	7	8	product
Stainless steel, martensitic, 15-5PH, wrought, H1075	0,116	0,0193	0,0012	0,13	0,386	0,0258	0,0043	2,76E-04	1,22
Stainless steel, martensitic, 17-4PH, cast, H1000	0,12	0,0202	0,0012	0,136	0,364	0,0258	0,0043	2,64E-04	1,49
Stainless steel, martensitic, 17-4PH, cast, H1100	0,111	0,0252	0,0013	0,175	0,336	0,0257	0,0059	3,04E-04	9,25
Stainless steel, martensitic, 17-4PH, wrought, H1025	0,134	0,0225	0,0014	0,122	0,406	0,0258	0,0043	2,64E-04	1,33
Stainless steel, martensitic, 17-4PH, wrought, H1075	0,118	0,0197	0,0012	0,155	0,393	0,0258	0,0043	2,64E-04	2,89
Stainless steel, martensitic, AISI 420F, wrought	0,0889	0,109	0,0014	0,136	0,335	0,0258	0,0316	4,05E-04	69,82
Stainless steel, martensitic, Custom 450, wrought, H1000	0,14	0,0279	0,0017	0,123	0,47	0,0265	0,0053	3,28E-04	4,11
Stainless steel, martensitic, Custom 450, wrought, H1050	0,124	0,0248	0,0015	0,187	0,417	0,0265	0,0053	3,28E-04	20,65
Stainless steel, martensitic, Custom 450, wrought, H1100	0,0982	0,0195	0,0012	0,285	0,329	0,0265	0,0053	3,28E-04	66,07
Stainless steel, martensitic, PH 13-8Mo, wrought, H1100	0,127	0,0226	0,0015	0,161	0,457	0,0259	0,0046	3,13E-04	8,11

Top material

- Stainless steel, martensitic, AISI 420F, wrought
- But: search phase reveals:
  - 420F will withstand only minor cold work. Radical forming operations will result in cracking.
- Stainless steel, martensitic, Custom 450, wrought, H1050
  - *This alloy is a martensitic stainless that combines corrosion resistance similar to 304, easy fabrication and single step age hardenability yielding good strength and ductility. It possesses a yield strength that is roughly 3 times the strength of standard 304 stainless.*

TA-DAAA!!!

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Thank you for your attention
תודה לך על תשומת הלב

Lubrication Journal...UK

"When it comes to the future,
there are three kinds of people :
those who let it happen,
those who make it happen, and
those who wonder what happened"

(John M. Richardson, Jr.)