Engineering Tripos Part IA **First Year**

Paper 2 - MATERIALS
HANDOUT 5

8. Manufacturing Processes, Process Selection

8.1 Hierarchy of Manufacturing Processes
8.2 Process Selection
Process Attributes
Procedure for preliminary process selection

9. Environmental Impact of Materials

Life Cycle Assessment

This handout covers the materials for Examples Paper 4, Q.8-10

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References/software:

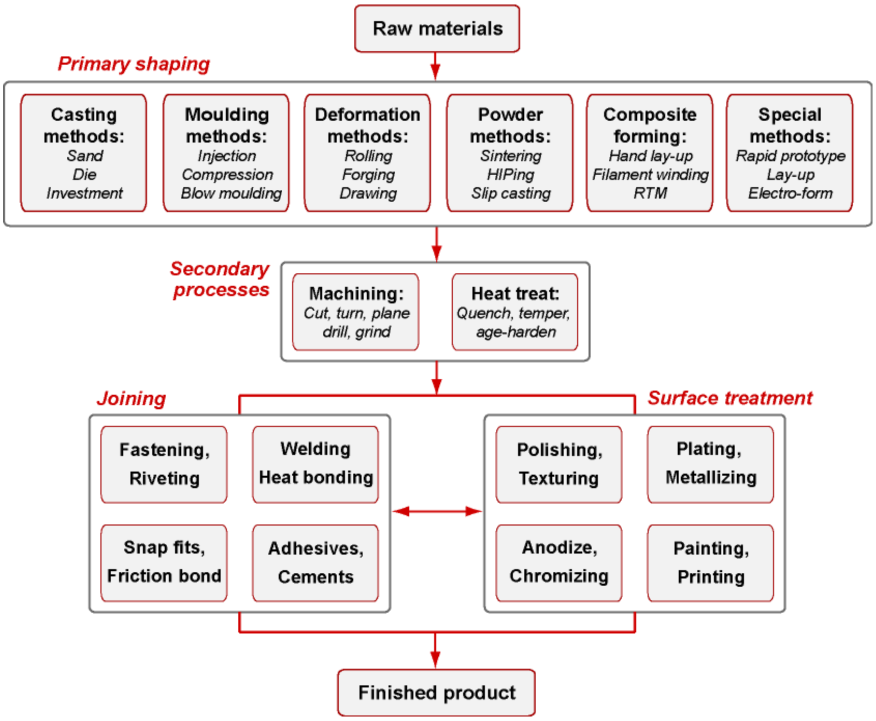
Materials: Engineering, Science, Processing and Design – Chapters 2, 18, 20
Ashby MF, Shercliff HR and Cebon D
(Butterworth-Heinemann, 1st, 2nd or 3rd edition)

Cambridge Engineering Selector (CES) – downloadable
(Process images and descriptions)

CD: Material Selection and Processing – on PWF
(Animations of manufacturing processes)

8. MANUFACTURING PROCESSES, PROCESS SELECTION

8.1 Hierarchy of Manufacturing Processes



Manufacturing processes are classified by:

- the *function* they provide
- the underlying *physics* of how they work.

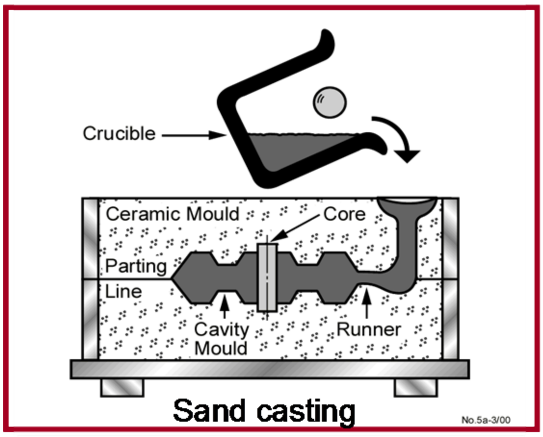
Top level hierarchy of process functions:

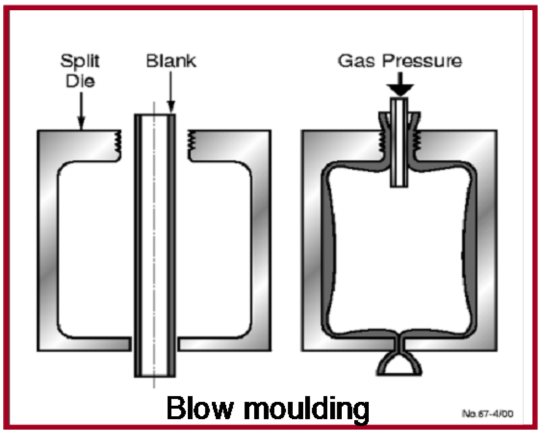
Primary shaping: turn raw material into components
Secondary processes: add features to components; modify bulk properties
Joining: assemble components into products
Surface treatment: modify surface properties

How do the processes work?

Engineers need a working knowledge of the main manufacturing processes.

There is no shortage of information to find this out (textbooks, Web, CES); even better: go and see manufacturing in action for yourself.





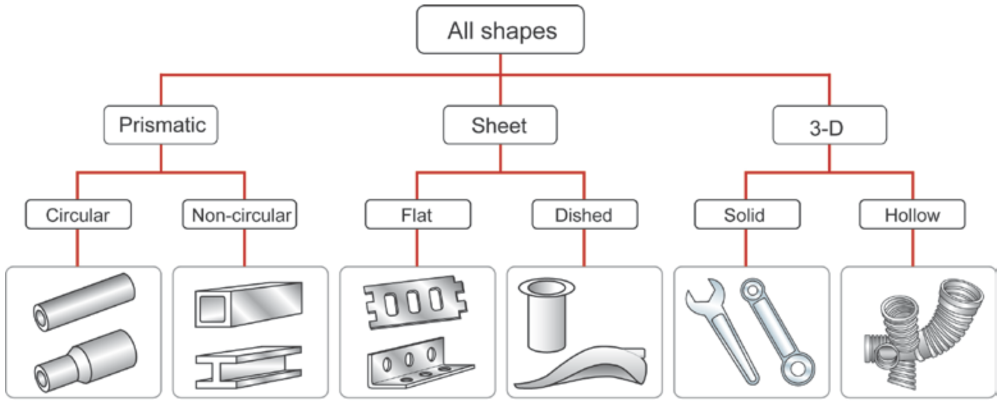
It is straightforward to summarise the *physical basis* of the different process families.

e.g. *primary shaping*:

casting: pour liquid (metal), solidify and cool, remove mould
forming: plastically deform solid (metal) to shape (hot or cold)
powder: fill die with powder (ceramic, metal) and hot press
moulding: viscous flow of molten polymer (or glass)

Choice of shaping process can be strongly influenced by *geometric characteristics* of the components being shaped.

Shape classification for components and products

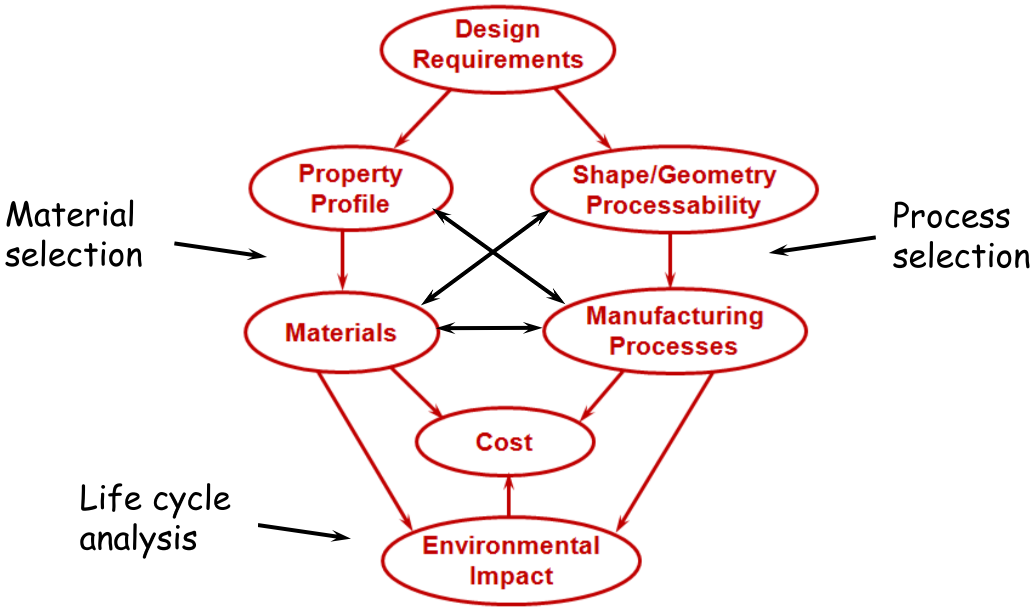


Each shaping process tends to be designed to produce certain shapes:

e.g. *rolling, extrusion*: prismatic shapes (continuous)
forging, powder, moulding: 3D shapes (batch)

8.2 Process Selection

Reminder: design-led view of materials and processes:



Recall for *material selection*: match material to the *"property profile"* required by the design.

Process selection: partly analogous, i.e. match features of the design to the *"attribute profile"* which processes can provide.

NB: Process selection applies separately to the three process classes:
shaping
joining
surface treatment

These do not compete with one another – they provide different functions and each has its own design requirements.

Here we mainly consider *primary shaping*.

Process Attributes

Definition: quantitative and qualitative data that define the physical capabilities of a process.

For primary shaping processes, the most important attributes are:

Material class: Materials to which process can be applied
Shape class: Shapes that the process is able to make

Mass: Limits on mass (or size) that the process can handle
Section thickness: Upper and lower dimensional limits

Tolerance: Dimensional precision
Roughness: Surface finish

Process Attribute Charts (p.22-25, Materials Databook)

Process Attribute Charts present the data graphically – the same methodology is used in the Cambridge Engineering Selector (CES) software.

Material - Process Compatibility (e.g. Shaping Metals)

Metals		**Sand Casting**	**Die Casting**	**Investment Casting**	**Rolling/ Forging**	**Extrusion**	**Sheet Forming**	**Powder Methods**	**Machining**
Ferrous	Cast Irons	•	•	•					
	Medium/High Carbon Steels	•		•	•			•	•
	Low Carbon Steels	•		•	•		•	•	•
	Low Alloy/Stainless Steels	•	•	•	•		•	•	•
Non-ferrous	Aluminium, Copper, Lead, Magnesium, Zinc Alloys	•	•	•	•	•	•	•	•
	Nickel Alloys	•	•	•	•		•	•	•
	Titanium Alloys		•		•	•	•	•	•

Material – process compatibility depends on the physical nature of the process, and whether the material has suitable properties.

Examples of physical process limits:

(1) *Metals*: Many shaping and joining processes available
Some limits with high T_m metals

(2) *Ceramics*: Only powder methods available for shaping (high T_m)
Difficult to join

(3) *Glasses*: Viscous at moderate T ⇒ can hot form or mould
Difficult to join

(4) *Polymers*: Many moulding and joining processes available
Thermoplastics: Can be softened ⇒ can hot form, weld (and recycle)
Thermosets: Must be moulded to net shape

(5) *Composites*: A few dedicated net-shaping processes
Difficult to join

(6) *Natural materials*: Usually machined to shape; some woods hot formed;
Easy to join: adhesives or mechanical

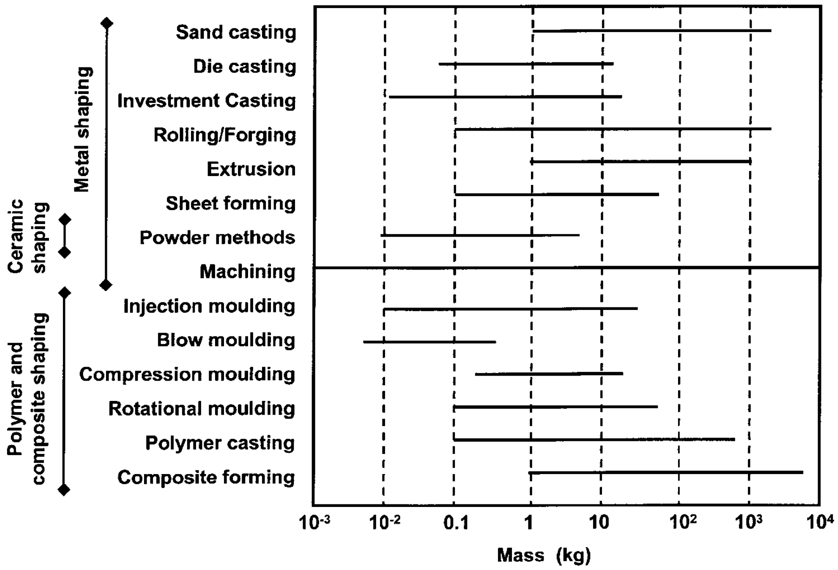
Shape - Process Compatibility

Not in Databook – just consider 3 shape classes presented earlier:

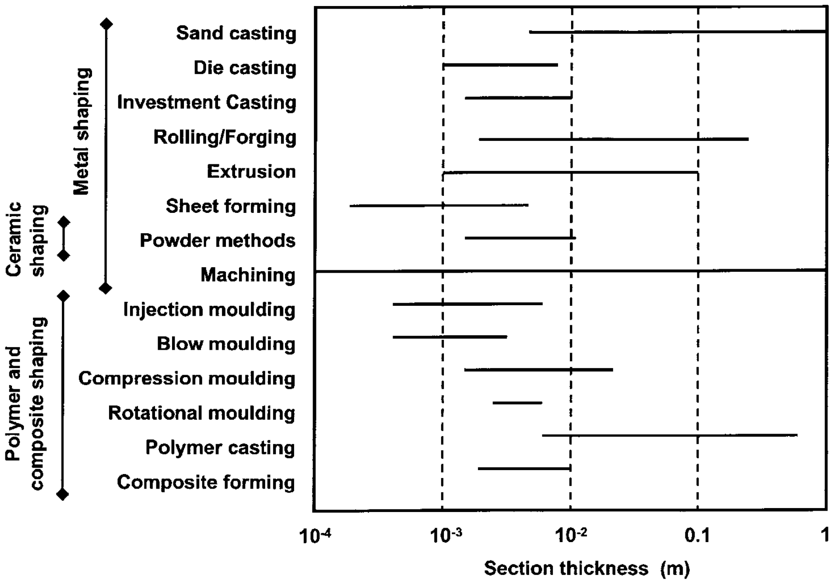
Prismatic: rolling, extrusion
Sheet: sheet metal forming
3D: casting, forging, powder, moulding, machining

Charts 1 + 2: Mass & Section Thickness

Process Selection Chart 1: Mass



Process Selection Chart 2: Section thickness

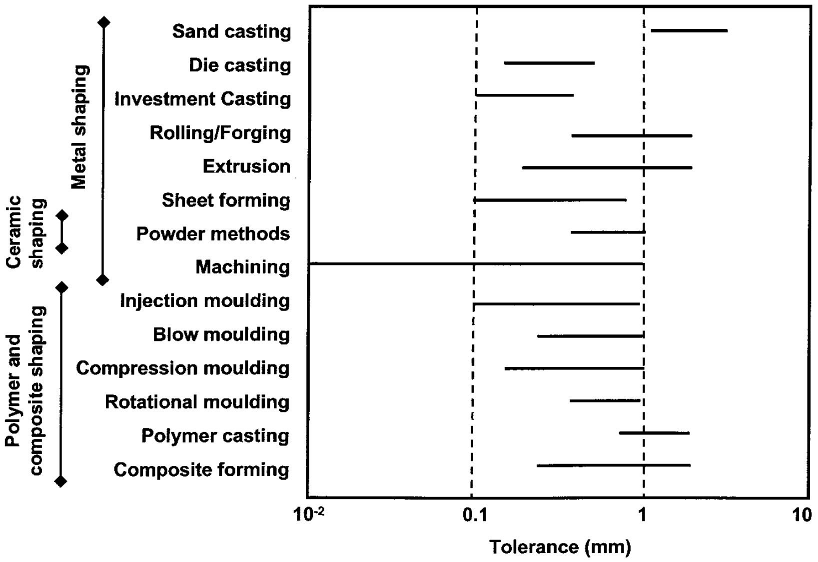


Notes:

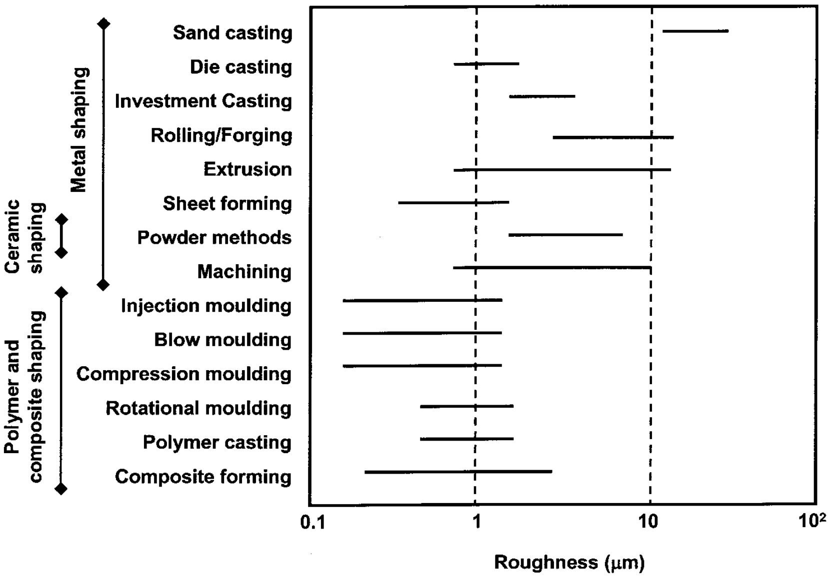
- Size and thickness only discriminating at the extremes
- Wide range of size and thickness can be achieved by almost all processes
- Machining used for shaping at all length scales

Charts 3 + 4: Tolerance & Roughness

Process Selection Chart 3: Tolerance



Process Selection Chart 4: Roughness



Notes:

- Polymers give a smooth finish, but poor dimensional accuracy
- Tolerance & roughness more discriminating between processes
- Machining after shaping used in metals to reach target precision and finish
- Expensive to over-specify precision and finish

Procedure for preliminary process selection

Stage 1: Screening

Eliminate processes that are unable to meet one or more of the design requirements.

(1) Assemble information about the design requirements:

- material class, shape class
- approximate mass, section thickness and tolerances
- required surface finish

(2) Plot on the Process Attribute Charts to identify processes that have the required attributes.

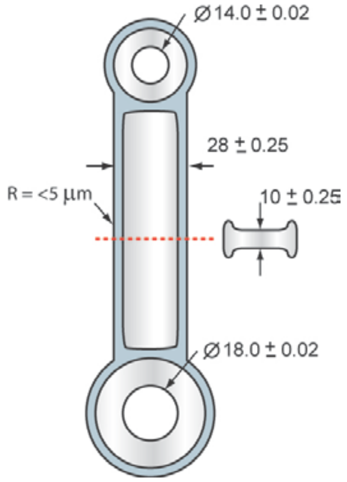
(3) Consider "stacking" of processes to bypass problems (e.g. if shaping processes fail on tolerance or roughness, consider shaping then machining).

NB: the charts show the “normal” viable ranges for each process – operating outside these ranges may be feasible, but probably only at a cost penalty.

Example: *Process selection for a connecting rod*

Assume preliminary material selection has been made, based on:

- resistance to buckling
- fatigue strength, at minimum weight
- specified length and approximate cross-section dimensions



Chosen material:

Process route?

Shape:

Mass (from approx. dimensions, and density):

Minimum section thickness:

Tolerance:

Surface roughness:

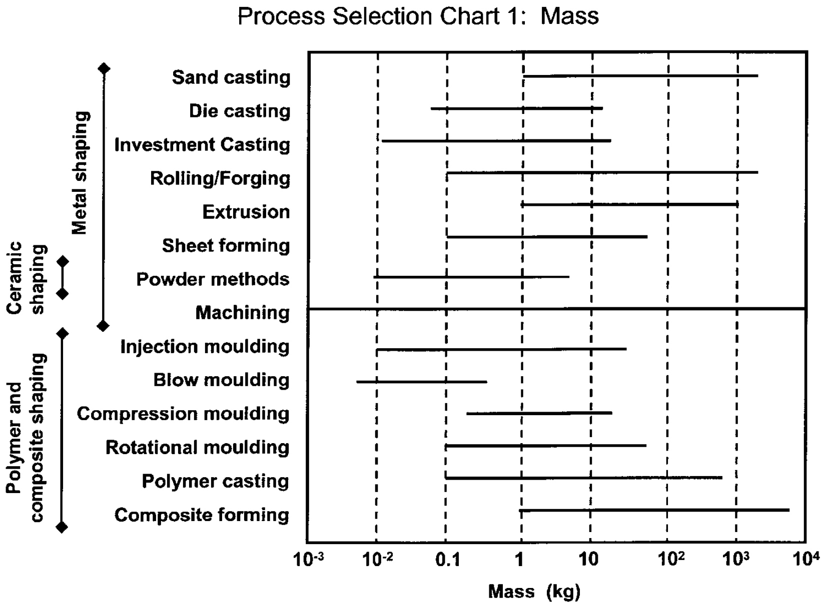
Material - Process Compatibility

Most metal shaping processes OK: eliminate *die casting* and *extrusion*.

Shape - Process Compatibility

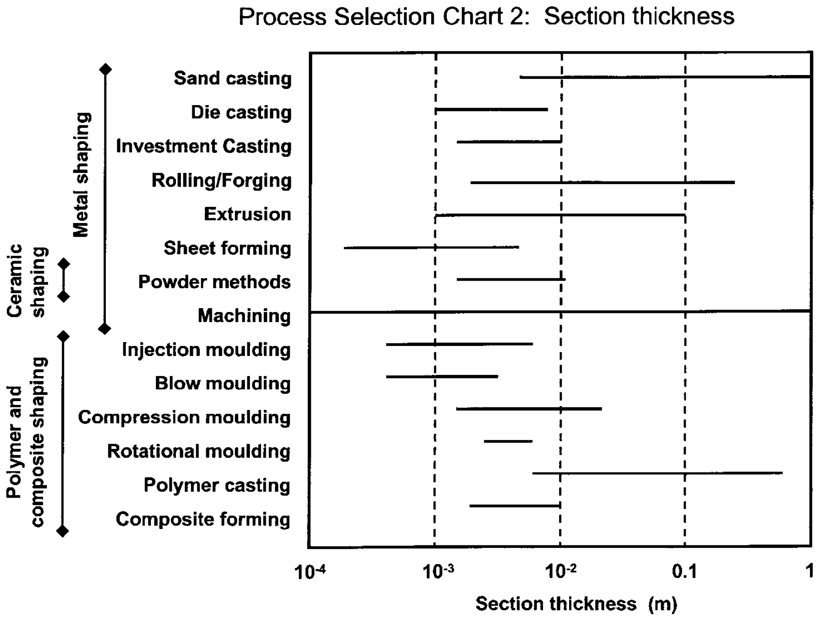
3D shape: eliminate prismatic processes (*rolling*, *extrusion*) & *sheet forming*.

Chart 1: Mass



Sand casting: outside normal viable range

Chart 2: Section Thickness

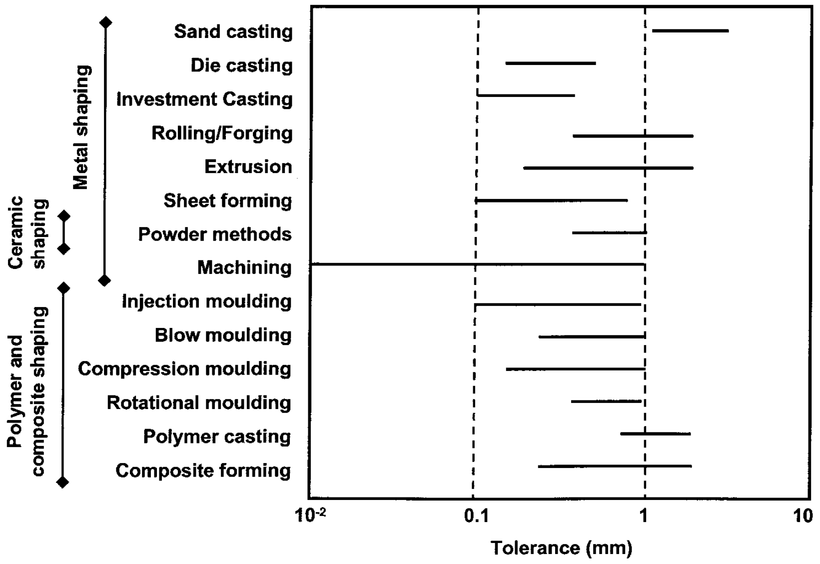


Die casting: outside normal viable range

Investment casting/powder methods: on limit of normal range

Chart 3: Tolerance

Process Selection Chart 3: Tolerance

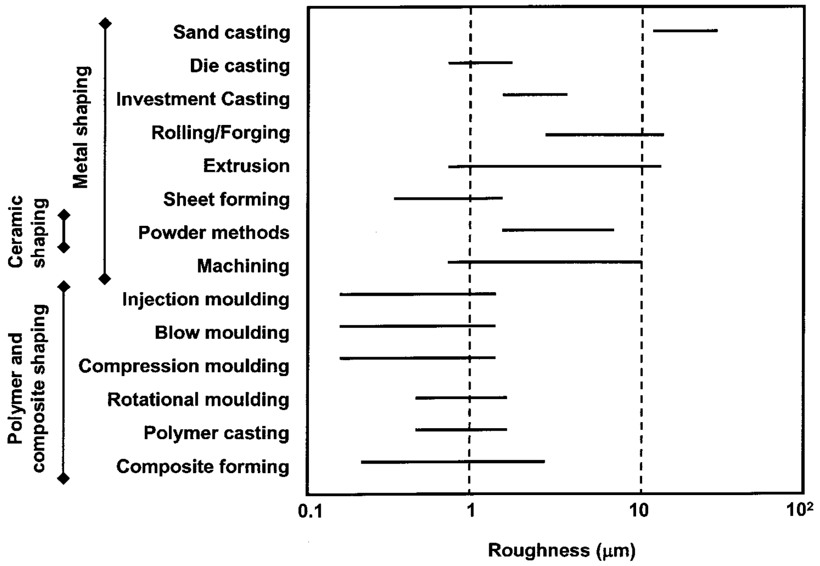


Sand casting/forging/powder: unable to achieve target tolerance of 0.25mm
- must follow by *machining*

To achieve bore hole tolerance of 0.02mm – must use *machining*

Chart 4: Roughness

Process Selection Chart 4: Roughness



Sand casting: unable to achieve target roughness of 5µm
- must follow by *machining*

Results of Screening Stage

Possible processes:

Process	*Comments*
Sand casting + machining	Marginal on mass; machine for tolerance/roughness
Investment casting	OK on all criteria
Forging + machining	Machine for tolerance
Powder methods + machining	Machine for tolerance
Machine from solid	Machining can be used for shaping and finishing

(+ machining of bore holes in all cases)

Final selection based on *cost*.

Stage 2: Cost-based ranking

Manufactured cost can be estimated approximately for mass-produced, net-shaped products.

The total cost of a component depends on three contributions:

"Material" Cost, C_m - including "consumables"

"Tooling" Cost, C_c - dedicated tooling (dies, moulds etc)

"Overhead" Cost, $\dot{C}_L$ - labour, energy, share of capital

The relative importance of these depends on:

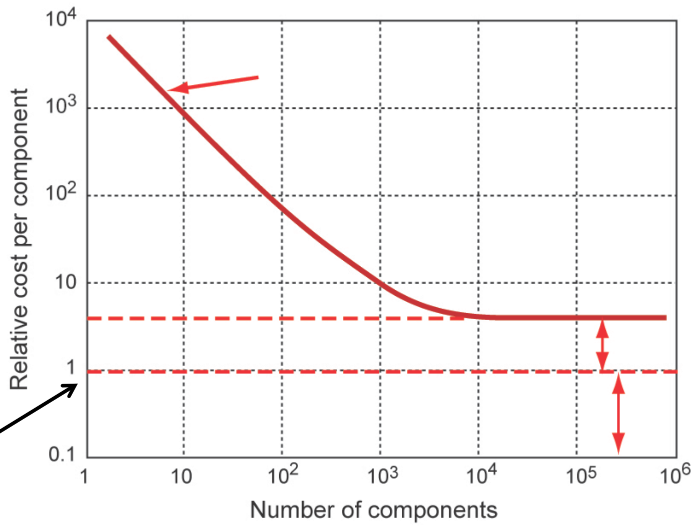
Batch size, n - total number being made

Production rate, $\dot{n}$ - number/hour which can be made

General cost equation

Cost per part: $$C = C_m + \underset{\uparrow}{\frac{C_c}{n}} + \underset{\uparrow}{\frac{\dot{C}_L}{\dot{n}}}$$

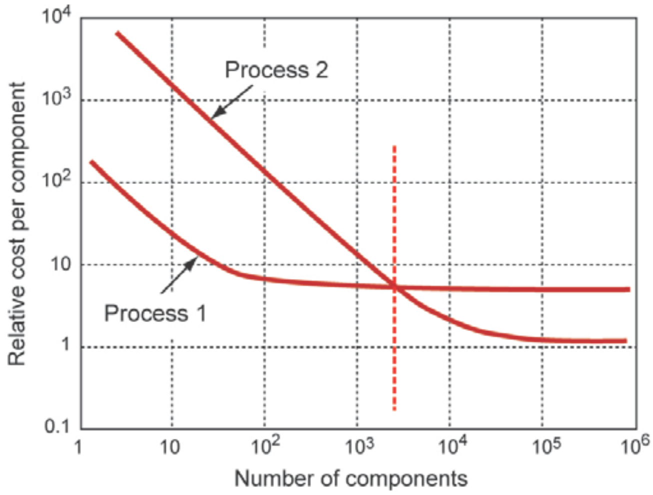
Shares of tooling and overhead, per part



Normalise to C_m,
i.e. (C/C_m)

Economic batch size

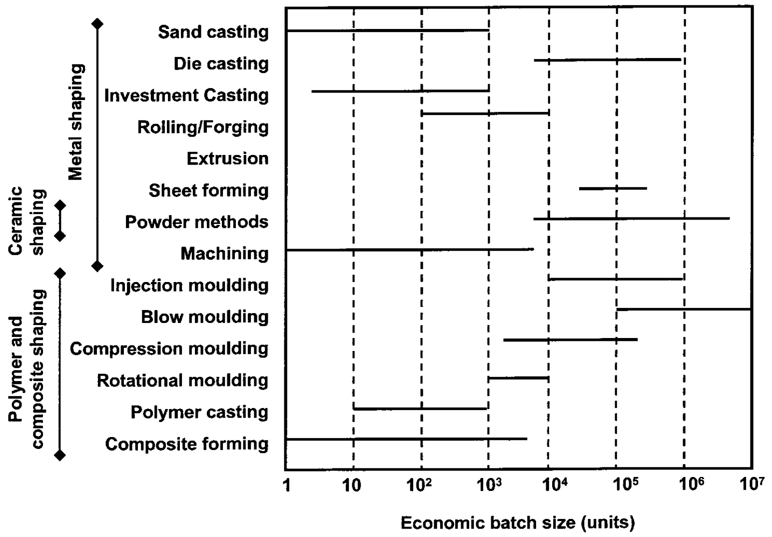
The cost equation allows competing processes to be ranked approximately in order of increasing cost. The ranking depends on the batch size.



Experience shows that each process has a characteristic range of batch sizes for which it is usually competitive.

A preliminary cost assessment can made on the basis of this range of *economic batch size*.

Charts 5: Economic Batch Size (also in Materials Databook)


Process Selection Chart 5: Economic batch size

Production outside each range is not excluded of course – but it provides an initial indicator that there may be a cost penalty.

Example: *Cost-based selection for a connecting rod*

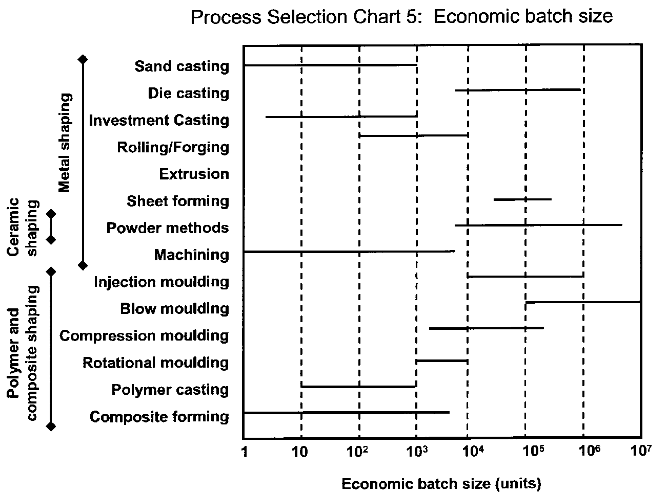
Candidate processes (from screening stage):

- investment casting
- sand casting
- hot forging
- powder methods

\+ machining

Target batch size:

(1) Preliminary assessment: Economic batch size



Sand casting/investment casting: usually economic for smaller batches

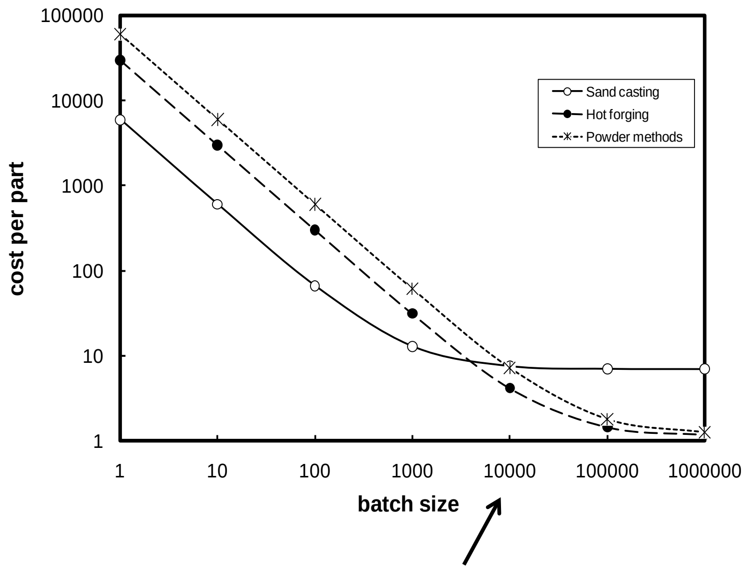
Forging/powder methods: both OK

(2) Detailed cost analysis: Cost equation

Compare *Forging*, *Powder Methods* and one casting option, *Sand Casting*.

	Sand Casting	Hot Forging	Powder Methods
Material Cost, C_m	1	1	1
Tooling Cost, C_c	6,000	30,000	60,000
Overhead Cost, $\dot{C}_L$ (hr^{-1})	60	30	10
Production rate, $\dot{n}$ (hr^{-1})	10	200	50

Substitute into cost equation, and plot cost per part against batch size n



Cost ranking for target batch size of 10,000 (cheapest first):

Hot forging
Powder methods
Sand casting

University of Cambridge

Engineering Tripos, Part IA **Paper 2: Materials**

HANDOUT 5

Environmental Impact of Materials, Life Cycle Assessment

M.F. Ashby
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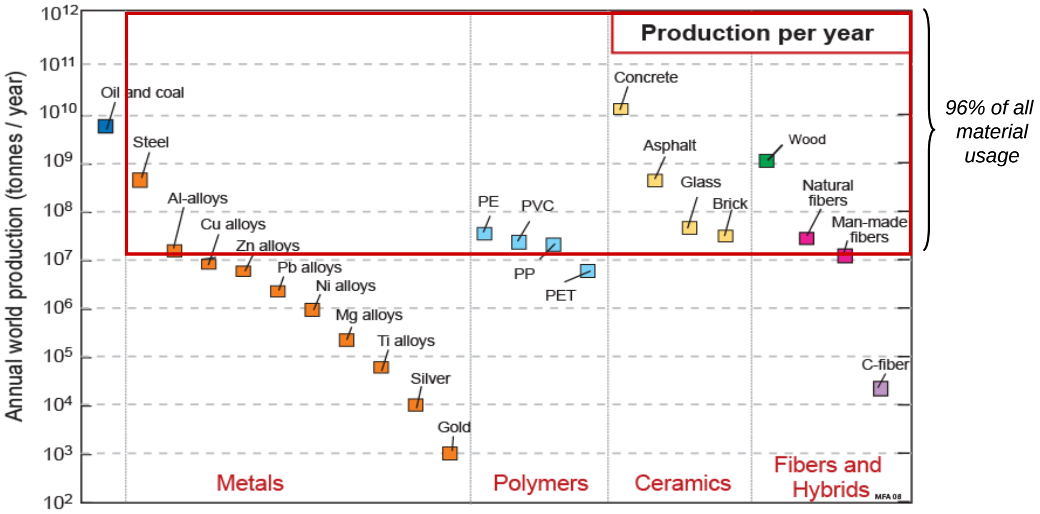
March 2014

Materials: global annual production

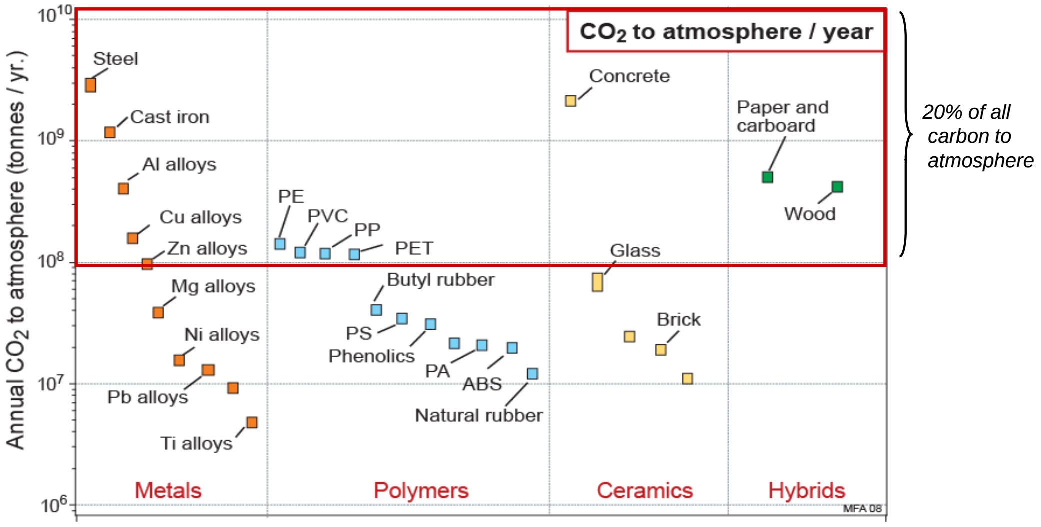
Concern 1 **: Resource consumption**



- **Construction materials:** **completely dominant**
- **Steel:** **10 x greater consumption than all other metals combined**
- **Polymers**: **total approaching same consumption as steel**

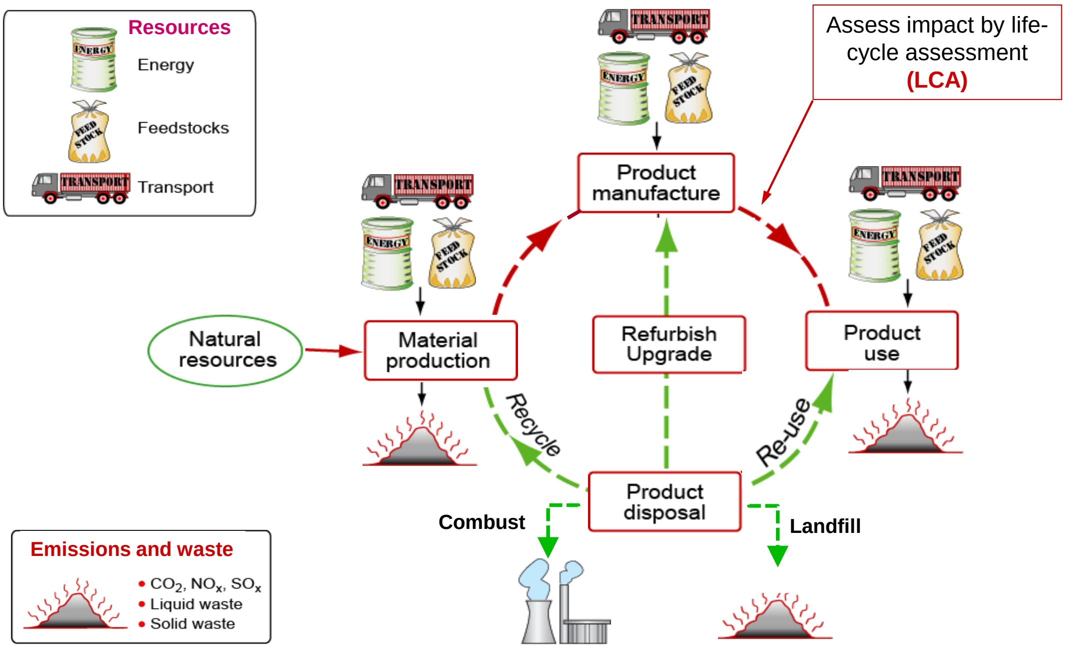
Carbon release to atmosphere

Concern 2 **: CO_2 emission (and corresponding energy consumption)**



- **Environmental impact of materials (CO_2 and energy consumption):**
  significant proportion of global CO_2
  dominated by concrete, polymers, steel, aluminium, paper, wood

The product life-cycle



Life cycle assessment (LCA)

Typical LCA output (Boustead model)

Aluminium cans, per 1000 units

Resource consumption

Bauxite	***59***	***kg***
Oil fuels	***148***	***MJ***
Electricity	***1572***	***MJ***
Energy in feedstocks	***512***	***MJ***
Water use	***1149***	***kg***

Emissions inventory

Emissions: CO_2	***211***	***kg***
Emissions: CO	***0.2***	***kg***
Emissions: NO_x	***1.1***	***kg***
Emissions: SO_x	***1.8***	***kg***
Particulates	***2.47***	***kg***

Impact assessment

Ozone depletion potential	***0.2×10^{-9}***
Global warming potential	***1.1×10^{-9}***
Acidification potential	***0.8×10^{-9}***
Human toxicity potential	***0.3×10^{-9}***

Roll up into
a single
"eco-indicator" ?

- Full LCA *time consuming, expensive*, requires great *detail,* and *subjective* (relative weighting of impacts)
- What is a designer supposed to do with the numbers ?

- Need **simple approach**: choose a single measure of impact – ***energy** or **CO_2***

Why energy or CO_2 ?

- **Kyoto Protocol (1997) and successors: international agreement to limit greenhouse gases**
- **IPCC report (2007) identifies carbon as principal cause of climate change**
- **EU and EPA Directives such as the *Energy-using Product (EuP) Directive* (2006)**

- **Practicality: CO_2 and Energy are related and understood by the public**

e.g. Cars: use-energy and CO_2 cited

Fuel economy figures:
Consumption: 6 – 11 litre / 100km
CO_2 emissions: 158 – 276 g / km

Appliances: use-energy cited

Efficiency rating: A
Volume 0.3 m^3
330 kWh / year

Examples: energy consumption of products

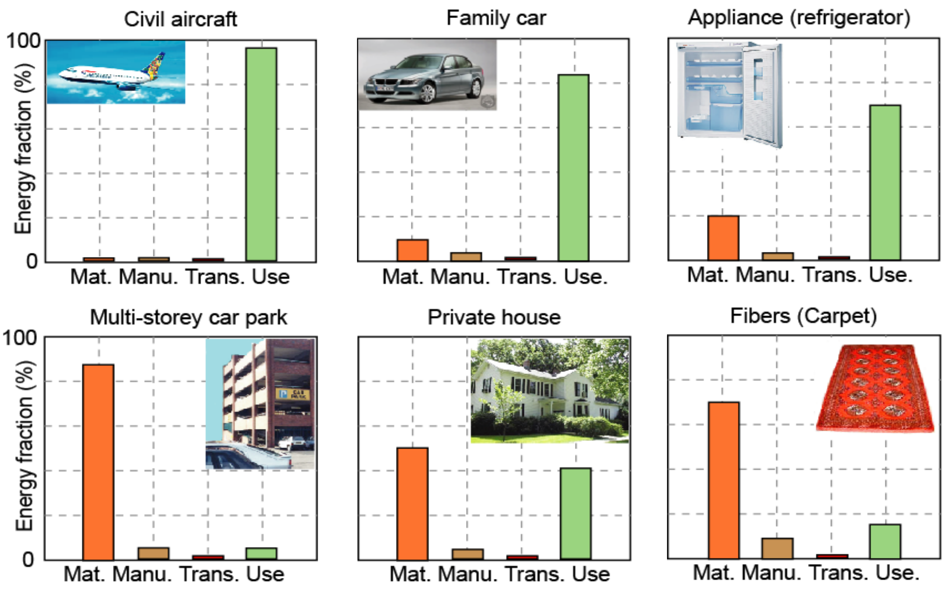
Which life phase dominates?

Examples of EuPs

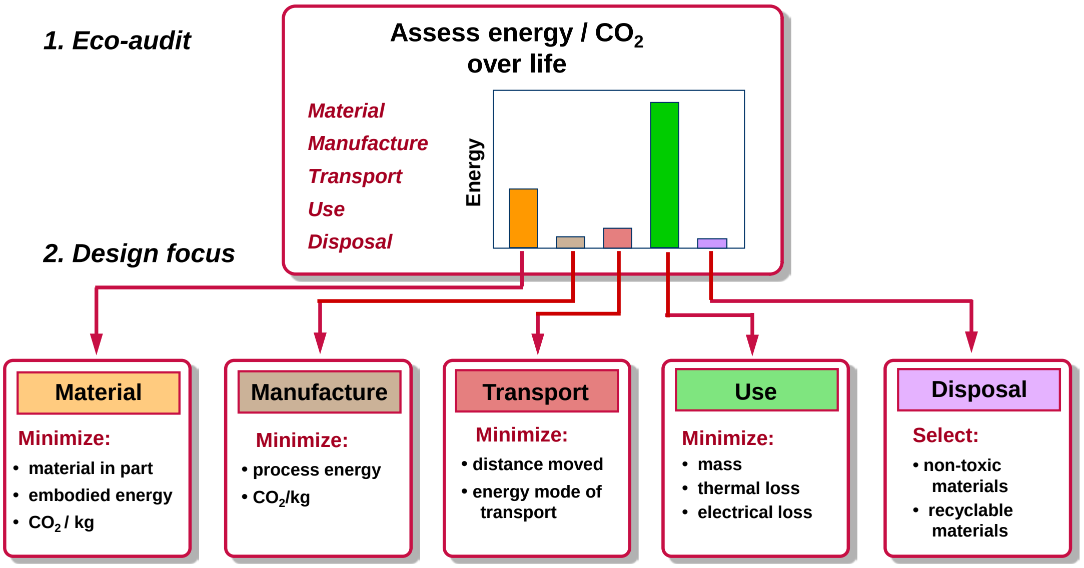
Use phase dominant

Other products

A more mixed picture



Strategy for material selection and design



1. Eco-audit

Assess energy / CO_2 over life

Material
Manufacture
Transport
Use
Disposal

2. Design focus

Material

Minimize:
- material in part
- embodied energy
- CO_2 / kg

Manufacture

Minimize:
- process energy
- CO_2/kg

Transport

Minimize:
- distance moved
- energy mode of transport

Use

Minimize:
- mass
- thermal loss
- electrical loss

Disposal

Select:
- non-toxic materials
- recyclable materials

CES Eco-audit methodology

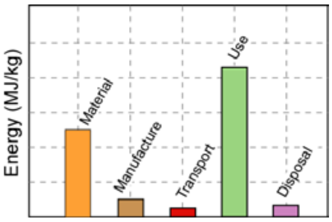
Inputs:

User inputs
- *Bill of materials*
- *Shaping process*
- *Transport needs*
- *Duty cycle*
- *etc*

Eco database
- *Embodied energies*
- *Process energies*
- *CO_2 footprints*
- *Unit transport energies*
- *etc*

CES Eco audit

Outputs:



Summary
- *Summary sheet*
- *Detailed breakdown*
- *Life phase energies*
- *Life carbon footprints*
- *etc*

CES Eco-data for a material

Polyethylene terephthalate (PET)

Primary material production: energy, CO2 and water				
Embodied energy, primary production	80	-	88	MJ/kg
CO2 footprint, primary production	2.2	-	2.5	kg/kg
Water usage	* 15	-	44	l/kg
Eco-indicator	369	-	400	millipoints / kg
Material processing: energy				
Polymer molding energy	* 9.4	-	10	MJ/kg
Polymer extrusion energy	* 3.6	-	4	MJ/kg
Material processing: CO2 footprint				
Polymer molding CO2	* 0.75	-	0.83	kg/kg
Polymer extrusion CO2	* 0.29	-	0.32	kg/kg
Material recycling: energy, CO2 and recycle fraction				
Embodied energy, recycling	33	-	37	MJ/kg
CO2 footprint, recycling	0.93	-	1	kg/kg
Recycle fraction in current supply	20	-	22	%
Toxicity rating	Non-toxic			
Combust for energy recovery	True			
Biodegrade	False			

User inputs:
Material breakdown:
  mass
  process

CES Transport and Use Data

Transport types

- Sea freight
- River / Canal freight
- Rail freight
- 32 tonne truck
- 14 tonne truck
- Light goods vehicle
- Air freight - short haul
- Air freight - long haul
- Helicopter (Eurocopter AS 35)

Data:
MJ / tonne.km
CO_2 / tonne.km

User inputs:
mass
transport distance

Use: energy conversion

- **Fossil fuel to thermal**
- **Fossil fuel to mechanical**
- **Electric to thermal**
- **Electric to mechanical**

Data:
Conversion efficiencies

User inputs:
power rating
duty cycle
product life

Example 1: CES Eco-audit of jug kettle

2 kW jug kettle

Bill of materials

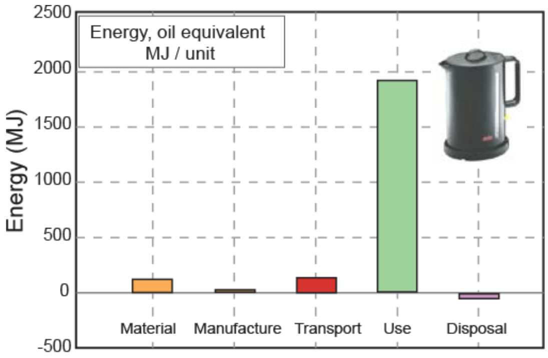
Component	Material	Process	Mass (kg)
Kettle body	Polypropylene (PP)	Polymer molding	0.86
Heating element	Nickel-chromium alloys	Forging, rolling	0.026
Casing, heating element	Stainless steel	Forging, rolling	0.09
Cable sheath, 1 meter	Natural Rubber (NR)	Polymer molding	0.06
Cable core, 1 meter	Copper	Forging, rolling	0.015
Plug body	Phenolic	Polymer molding	0.037
Plug pins	Brass	Forging, rolling	0.03
Packaging, padding	Rigid polymer foam, MD	Polymer molding	0.015
Packaging, box	Cardboard	Construction	0.125

Transport:

- 12,000 km, air freight
- 250 km 14 tonne truck

Use:

- Electric-to-thermal
- 6 minutes per day
- 300 days per year
- 3 years



Conclude:

- Little gained by change in material
- Much to be gained by re-design (e.g. double wall with insulating foam or vacuum)

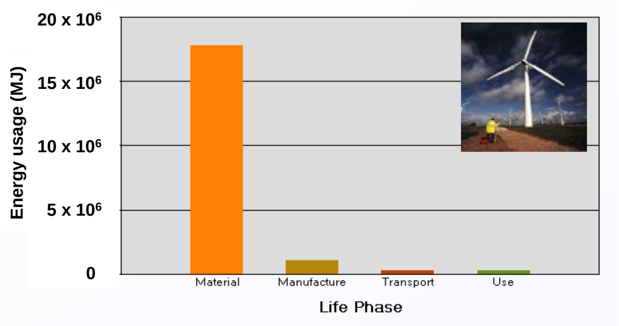
Example 2: CES Eco-audit of 2 MW wind turbine

Wind turbine: bill of materials

Component	Component	Material	Process	Mass (kg)
Tower (165 tonnes)	Structure	Low carbon steel	Forging, rolling	164,000
	Cathodic protection	Zinc	Casting	203
Nacelle (61 tonnes)	Gears	Stainless steel	Forging, rolling	19,000
	Generator, core	Iron (low C steel)	Forging, rolling	9,000
	Generator, conductors	Copper	Forging, rolling	1,000
	Transformer, core	Iron	Polymer molding	6,000
	Transformer, conductors	Copper	Forging, rolling	2,000
	Transformer, conductors	Aluminum	Forging, rolling	1,700
	Cover	GFRP	Composite forming	4,000
	Main shaft	Cast iron	Casting	12,000
	Other forged components	Stainless steel	Forging, rolling	3000
	Other cast components	Cast iron	Casting	4,000
Rotor (34 tonnes)	Blades	CFRP	Composite forming	24,500
	Iron components	Cast iron	Casting	2,000
	Spinner	GFRP	Composite forming	3,000
	Spinner	Cast iron	Casting	2,200
Foundations (832 tonnes)	Pile and platform	Concrete	Construction	805,000
	Steel	Low carbon steel	Forging, rolling	27,000
Transmission	Conductors	Copper	Forging, rolling	254
	Conductors	Aluminum	Forging, rolling	72
	Insulation	Polyethylene	Polymer extrusion	1,380

Example 2: CES Eco-audit of 2 MW wind turbine

1. Energy balance



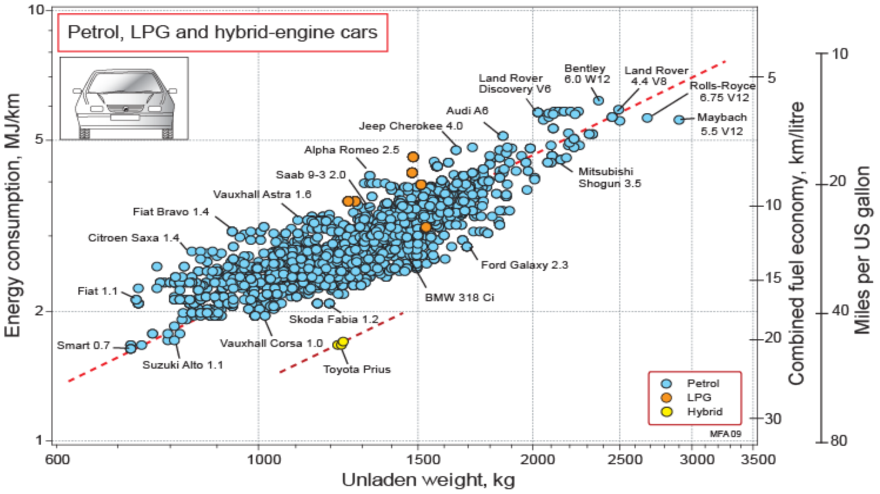
Phase	Construction energy (MJ)	Construction CO$_2$ (kg)
Material	1.8×10^7	1.3×10^6
Manufacture	1.0×10^6	9.6×10^4
Transport	2.5×10^5	1.6×10^4
Use (maintenance)	2.3×10^5	1.9×10^4
Total	**1.9×10^7**	**1.4×10^6**

2. Energy payback time

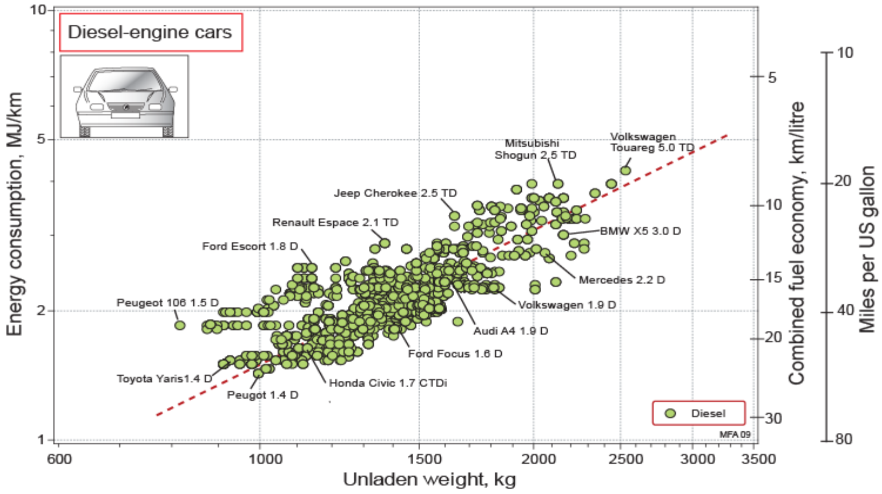
Energy generated per year at 35 % capacity factor = **2.1×10^7 MJ / yr**

Payback time = $1.9 \times 10^7 / 2.1 \times 10^7$ = 0.90 years = **10.9 months**

Example 3 - cars: use energy vs. mass (petrol)



Example 3 - cars: use energy vs. mass (diesel)



Petrol : Energy in MJ/km ~ 2.1 x 10^{-3} x mass in kg

Diesel : Energy in MJ/km ~ 1.7 x 10^{-3} x mass in kg

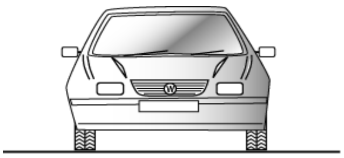
Examples 3 - Eco audit for car: materials vs. use

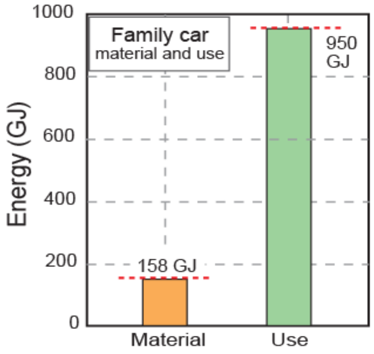
Bill of materials

Material	Mass (kg)	Material energy, MJ/kg*
Steel *(Low alloy steel)*	950	35
Aluminum *(Cast aluminum alloy)*	438	210
Thermoplastic polymers *(PU, PVC)*	148	80
Thermosetting polymers *(Polyester)*	93	88
Elastomers *(Butyl rubber)*	40	110
Glass *(Borosilicate glass)*	40	15
Other metals *(Copper)*	61	72
Textiles *(Polyester)*	47	47
Total mass	1800	

Use:

- 25,000 km/year
- 10 years
- 3.8 MJ/km

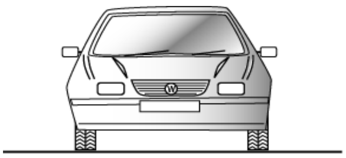




Examples 3 - Eco audit for car: material substitution

What is the life cycle impact of a material substitution?

Car bumper



Steel bumper

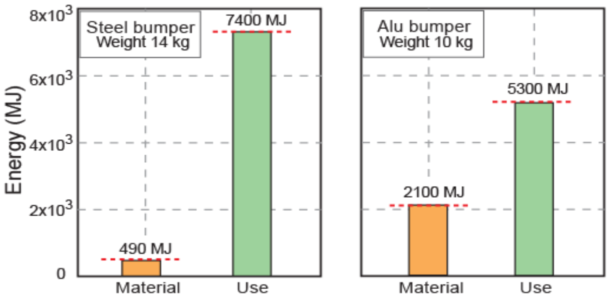
Embodied energy: 35 MJ/kg

Mass: 14 kg

Aluminium bumper

Embodied energy: 210 MJ/kg

Mass: 10 kg



Total over 250,000 km :

7890 MJ

Total over 250,000 km :

7400 MJ

Summary

- **Materials impact on the environment significant:**
  - very large tonnages (notably construction), and exponential growth
  - embodied energy of material production
  - energy consumption during manufacture, transport, use
  - disposal: landfill, re-use or recycle?
- **Full Life Cycle Assessment (LCA)**
  - expensive, time-consuming, subjective
- **Simple Eco-audit**
  - single measure of impact (energy, or CO_2)
  - quick, approximate overview of impact of products
  - identify dominant life phase: production, manufacture, transport, use, disposal
- **Benefits**
  - focus design on effective reduction of environmental impact
  - reduce mis-information, promote more balanced public understanding

Further Reading:

- Ashby M.F., Shercliff H.R. and Cebon D., “Materials: engineering, science, processing and design”, Chapter 20
- Ashby M.F., “Materials and the Environment”
- Mackay D., “Sustainable energy: without the hot air” (www.withouthotair.com)
- Allwood J.M. And Cullen J., “Sustainable materials: with both eyes open” (www.withbotheyesopen.com)