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)
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:
- rolling, extrusion: prismatic shapes (continuous)
- forging, powder, moulding: 3D shapes (batch)

8.2 Process Selection

Reminder: design-led view of materials and processes:

Material selection

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)

<table>
<thead>
<tr>
<th>Metals</th>
<th>Cast Irons</th>
<th>Die Casting</th>
<th>Investment Casting</th>
<th>Rolling/Forging</th>
<th>Extrusion</th>
<th>Sheet Forming</th>
<th>Powder Methods</th>
<th>Machining</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferrous</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Medium/High Carbon Steels</td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low Carbon Steels</td>
<td>*</td>
<td>*</td>
<td>R</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low Alloy/Stainless Steels</td>
<td>*</td>
<td>*</td>
<td>R</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-ferrous</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Aluminium, Copper, Lead, Magnesium, Zinc Alloys</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Nickel Alloys</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Titanium Alloys</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
</tbody>
</table>

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 Tₘ metals
2. **Ceramics:** Only powder methods available for shaping (high Tₘ)
   - 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

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

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**

*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**

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

Possible processes:

<table>
<thead>
<tr>
<th>Process</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand casting + machining</td>
<td>Marginal on mass; machine for tolerance/roughness</td>
</tr>
<tr>
<td>Investment casting</td>
<td>OK on all criteria</td>
</tr>
<tr>
<td>Forging + machining</td>
<td>Machine for tolerance</td>
</tr>
<tr>
<td>Powder methods + machining</td>
<td>Machine for tolerance</td>
</tr>
<tr>
<td>Machine from solid</td>
<td>Machining can be used for shaping and finishing</td>
</tr>
</tbody>
</table>

(+ 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, $C_L$ - 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: $C = C_m + \frac{C_c}{n} + \frac{C_L}{\dot{n}}$

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 be made on the basis of this range of economic batch size.

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

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.

<table>
<thead>
<tr>
<th></th>
<th>Sand Casting</th>
<th>Hot Forging</th>
<th>Powder Methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Cost, $C_m$</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Tooling Cost, $C_c$</td>
<td>6,000</td>
<td>30,000</td>
<td>60,000</td>
</tr>
<tr>
<td>Overhead Cost, $C_i$ (hr⁻¹)</td>
<td>60</td>
<td>30</td>
<td>10</td>
</tr>
<tr>
<td>Production rate, $\eta$ (hr⁻¹)</td>
<td>10</td>
<td>200</td>
<td>50</td>
</tr>
</tbody>
</table>

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
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
**Concern 2: CO₂ emission (and corresponding energy consumption)**

20% of all carbon to atmosphere

- Environmental impact of materials (CO₂ and energy consumption):
  - Significant proportion of global CO₂ dominated by concrete, polymers, steel, aluminium, paper, wood

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**The product life-cycle**

- **Resources**
  - Energy
  - Feedstocks
  - Transport

- **Natural resources**

- **Emissions and waste**
  - CO₂, NOₓ, SO₂
  - Liquid waste
  - Solid waste

- **Assess impact by life-cycle assessment (LCA)**

- **Product disposal**
  - Combust
  - Landfill

- **Product use**
  - Refurbish
  - Upgrade

- **Product manufacture**

- **Material production**

- **Transport**

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### Typical LCA output (Boustead model)

**Aluminium cans, per 1000 units**

<table>
<thead>
<tr>
<th>Resource consumption</th>
<th>Emissions inventory</th>
<th>Impact assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Bauxite 59 kg</td>
<td>• Emissions: CO₂ 211 kg</td>
<td>• Ozone depletion potential 0.2 X 10⁻⁵</td>
</tr>
<tr>
<td>• Oil fuels 148 MJ</td>
<td>• Emissions: CO 0.2 kg</td>
<td>• Global warming potential 1.1 X 10⁻⁹</td>
</tr>
<tr>
<td>• Electricity 1572 MJ</td>
<td>• Emissions: NO₂ 1.1 kg</td>
<td>• Acidification potential 0.8 X 10⁻⁹</td>
</tr>
<tr>
<td>• Energy in feedstocks 512 MJ</td>
<td>• Emissions: SO₂ 1.8 kg</td>
<td>• Human toxicity potential 0.3 X 10⁻⁹</td>
</tr>
<tr>
<td>• Water use 1149 kg</td>
<td>• Particulates 2.47 kg</td>
<td></td>
</tr>
</tbody>
</table>

**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 *CO₂*

### Why energy or CO₂ ?

- **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**: CO₂ and Energy are related and understood by the public

#### e.g. Cars: use-energy and CO₂ cited

- Fuel economy figures:
  - Consumption: 6 – 11 litre / 100km
  - CO₂ emissions: 158 – 276 g / km

#### Appliances: use-energy cited

- Efficiency rating: A
  - Volume 0.3 m³
  - 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 / CO₂ over life

Material
Manufacture
Transport
Use
Disposal

Minimize:
• material in part
• embodied energy
• CO₂ / kg

Minimize:
• process energy
• CO₂/kg

Minimize:
• distance moved
• energy mode of transport

Minimize:
• mass
• thermal loss
• electrical loss

Select:
• non-toxic materials
• recyclable materials

2. Design focus

Material
Manufacture
Transport
Use
Disposal

Minimize:
• material in part
• embodied energy
• CO₂ / kg

Minimize:
• process energy
• CO₂/kg

Minimize:
• distance moved
• energy mode of transport

Minimize:
• mass
• thermal loss
• electrical loss

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
- CO₂ footprints
- Unit transport energies
- etc

Outputs:

CES Eco audit

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

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CES Transport and Use Data

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

Data:
- MJ / tonne.km
- CO₂ / 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

Bill of materials

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

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)

Energy, oil equivalent MJ / unit

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

Wind turbine: bill of materials

<table>
<thead>
<tr>
<th>Component</th>
<th>Component</th>
<th>Material</th>
<th>Process</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tower (165 tonnes)</td>
<td>Structure</td>
<td>Low carbon steel</td>
<td>Forging, rolling</td>
<td>164,000</td>
</tr>
<tr>
<td></td>
<td>Cathodic protection</td>
<td>Zinc</td>
<td>Casting</td>
<td>203</td>
</tr>
<tr>
<td>Nacelle (61 tonnes)</td>
<td>Gears</td>
<td>Stainless steel</td>
<td>Forging, rolling</td>
<td>19,000</td>
</tr>
<tr>
<td></td>
<td>Generator core</td>
<td>Iron (low C steel)</td>
<td>Forging, rolling</td>
<td>9,000</td>
</tr>
<tr>
<td></td>
<td>Generator, conductors</td>
<td>Copper</td>
<td>Forging, rolling</td>
<td>1,000</td>
</tr>
<tr>
<td></td>
<td>Transformer, core</td>
<td>Iron</td>
<td>Polymer molding</td>
<td>6,000</td>
</tr>
<tr>
<td></td>
<td>Transformer, conductors</td>
<td>Copper</td>
<td>Forging, rolling</td>
<td>2,000</td>
</tr>
<tr>
<td></td>
<td>Transformer, conductors</td>
<td>Aluminum</td>
<td>Forging, rolling</td>
<td>1,000</td>
</tr>
<tr>
<td></td>
<td>Cover</td>
<td>FRP</td>
<td>Composite forming</td>
<td>4,000</td>
</tr>
<tr>
<td></td>
<td>Main shaft</td>
<td>Cast iron</td>
<td>Casting</td>
<td>12,000</td>
</tr>
<tr>
<td></td>
<td>Other forged components</td>
<td>Stainless steel</td>
<td>Forging, rolling</td>
<td>3000</td>
</tr>
<tr>
<td></td>
<td>Other cast components</td>
<td>Cast iron</td>
<td>Casting</td>
<td>4,000</td>
</tr>
<tr>
<td>Rotor (34 tonnes)</td>
<td>Blades</td>
<td>CFRP</td>
<td>Composite forming</td>
<td>24,500</td>
</tr>
<tr>
<td></td>
<td>Iron components</td>
<td>Cast iron</td>
<td>Casting</td>
<td>2,000</td>
</tr>
<tr>
<td></td>
<td>Spinner</td>
<td>FRP</td>
<td>Composite forming</td>
<td>3,000</td>
</tr>
<tr>
<td>Foundations (832 tonnes)</td>
<td>Pile and platform</td>
<td>Concrete</td>
<td>Construction</td>
<td>805,000</td>
</tr>
<tr>
<td></td>
<td>Foundation</td>
<td>Steel</td>
<td>Low carbon steel</td>
<td>27,000</td>
</tr>
<tr>
<td></td>
<td>TRANSMISSION</td>
<td>Conductors</td>
<td>Copper</td>
<td>264</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Conductors</td>
<td>Aluminium</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Insulation</td>
<td>Polyethylene</td>
<td>1,380</td>
</tr>
</tbody>
</table>

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

1. Energy balance

![Energy usage graph]

<table>
<thead>
<tr>
<th>Phase</th>
<th>Construction energy (MJ)</th>
<th>Construction CO₂ (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>1.8 x 10⁷</td>
<td>1.3 x 10⁶</td>
</tr>
<tr>
<td>Manufacture</td>
<td>1.0 x 10⁷</td>
<td>9.6 x 10⁵</td>
</tr>
<tr>
<td>Transport</td>
<td>2.5 x 10⁶</td>
<td>1.6 x 10⁵</td>
</tr>
<tr>
<td>Use (maintenance)</td>
<td>2.3 x 10⁶</td>
<td>1.9 x 10⁵</td>
</tr>
<tr>
<td>Total</td>
<td>1.9 x 10⁷</td>
<td>1.4 x 10⁶</td>
</tr>
</tbody>
</table>

2. Energy payback time

Energy generated per year at 35% capacity factor = 2.1 x 10⁷ MJ / yr
Payback time = 1.9 x 10⁷ / 2.1 x 10⁷ = 0.90 years = 10.9 months
Example 3 - cars: use energy vs. mass (petrol)

- **Petrol**: Energy in MJ/km $\sim 2.1 \times 10^{-3}$ x mass in kg

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

- **Diesel**: Energy in MJ/km $\sim 1.7 \times 10^{-3}$ x mass in kg
Examples 3 - Eco audit for car: materials vs. use

**Bill of materials**

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

**Use:**
- 25,000 km/year
- 10 years
- 3.8 MJ/km

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Examples 3 - Eco audit for car: material substitution

What is the life cycle impact of a material substitution?

**Steel bumper**
- Embodied energy: 35 MJ/kg
- Mass: 14 kg

**Car bumper**

**Aluminium bumper**
- Embodied energy: 210 MJ/kg
- Mass: 10 kg

**Total over 250,000 km**:
- Steel bumper: 7890 MJ
- Aluminium bumper: 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 CO₂)
  - 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., “Materials and the Environment”
- Mackay D., “Sustainable energy: without the hot air” ([www.withouthotair.com](http://www.withouthotair.com))
- Allwood J.M. And Cullen J., “Sustainable materials: with both eyes open” ([www.withbotheyesopen.com](http://www.withbotheyesopen.com))