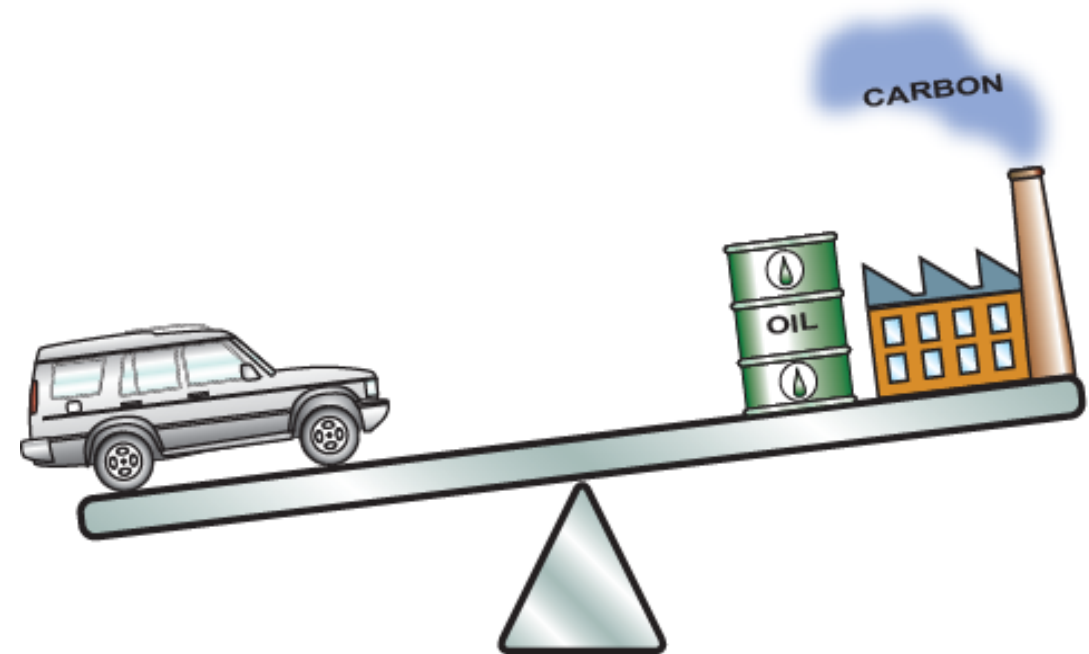




Eco Design and the Eco Audit Tool

introducing students to life-cycle thinking

Mike Ashby
Department of Engineering,
University of Cambridge



Learning objectives for this lecture unit

Ansys software mentioned	• Ansys Granta EduPack™, a teaching software for materials education
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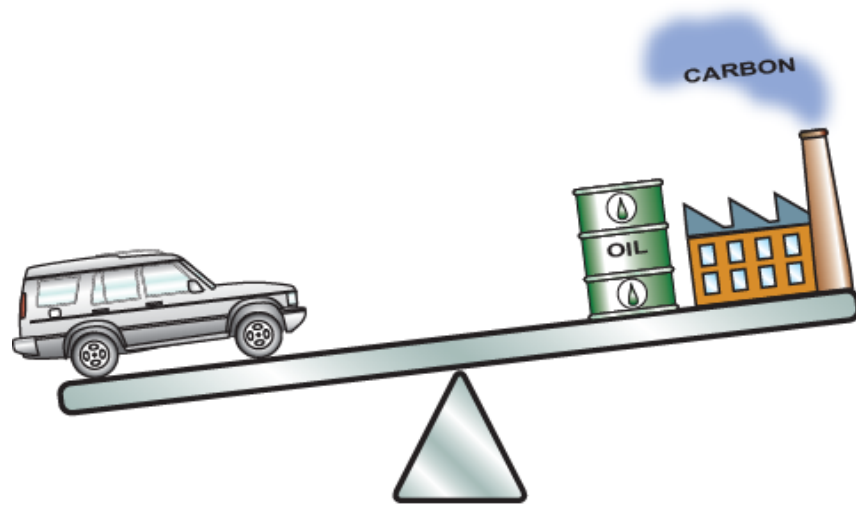
Intended Learning Outcomes

Knowledge and Understanding	Knowledge and understanding of the material life-cycle
Skills and Abilities	Ability to use Eco Audits in the design process
Values and Attitudes	Awareness that environmental design objectives influence material selection

Resources


- Text: “**Materials and the Environment**”, 3rd Edition by M.F. Ashby, Butterworth-Heinemann, Oxford 2021, UK. Chapters 1-10
- Text: “**Materials: engineering, science, processing and design**”, 4th Edition by M.F. Ashby, H.R. Shercliff and D. Cebon, Butterworth Heinemann, Oxford 2019, Chapter 20
- Text: “**Materials Selection in Mechanical Design**”, 5th Edition by M.F. Ashby, Butterworth Heinemann, Oxford, 2016. Chapter 14
- White Paper: [Ansys Granta EduPack software Eco Audit Tool](#)
- Poster: [Eco Design](#)

Agenda



- Eco data in the Ansys Granta EduPack software
- The product life-cycle
- Different strategies for eco-performance
- Performance index derivation: PET bottle
- Eco-selection with bubble charts
- LCA vs Eco Audit
- The Eco Audit tool
- Add your own data and records
- Comparisons of products over life-cycle
- The Advanced Eco Audit tool

Typical data records show eco-properties too

Acrylonitrile butadiene styrene (ABS)				
Datasheet view: All properties Show/Hide Find Similar				
Geo-economic data for principal component				
Annual world production, principal component	①	8.07e6		tonne/yr
Reserves, principal component	①	7.13e7	- 7.88e7	tonne
Primary material production: energy, climate change and water				
Climate change (CO2-eq) (virgin grade production)	①	* 3.51	- 3.87	kg/kg
Embodied energy (virgin grade production)	①	* 92.6	- 102	MJ/kg
Water usage	①	* 167	- 185	l/kg
Material processing: energy				
Polymer extrusion, embodied energy	①	* 8.06	- 8.93	MJ/kg
Polymer molding (injection, blow), embodied energy	①	* 21	- 24.2	MJ/kg
Machining, coarse, embodied energy	①	* 16.8	- 21.3	MJ/kg
Machining, fine, embodied energy	①	* 21.3	- 31.8	MJ/kg
Machining, grinding, embodied energy	①	* 25.7	- 42.3	MJ/kg
Material processing: climate change				
Polymer extrusion, climate change (CO2-eq)	①	* 0.53	- 0.589	kg/kg
Polymer molding (injection, blow), climate change (CO2-eq)	①	* 1.45	- 1.7	kg/kg
Machining, coarse, climate change (CO2-eq)	①	* 1.1	- 1.4	kg/kg
Machining, fine, climate change (CO2-eq)	①	* 1.39	- 2.08	kg/kg
Machining, grinding, climate change (CO2-eq)	①	* 1.68	- 2.77	kg/kg
Recycling and end of life				
Recycle	①	✓		
Functional recycle	①	✗		
Climate change (CO2-eq), recycling	①	* 1.16	- 1.28	kg/kg
Embodied energy, recycling	①	* 17.6	- 19.4	MJ/kg
Recycle fraction in current supply	①	1		%
Combust for energy recovery	①	✓		
Heat of combustion (net)	①	* 37.6	- 39.5	MJ/kg
Combustion CO2	①	* 3.06	- 3.22	kg/kg
Landfill	①	✓		
Biodegrade	①	✗		
Toxicity rating	①	Non-toxic		
A renewable resource?	①	✗		
Environmental notes				
The acrylonitrile monomer is nasty stuff, almost as poisonous as cyanide. Once polymerized with styrene it becomes harmless. ABS is FDA compliant, can be recycled, and can be incinerated to recover the energy it contains.				
Recycle mark ①				
 Other				

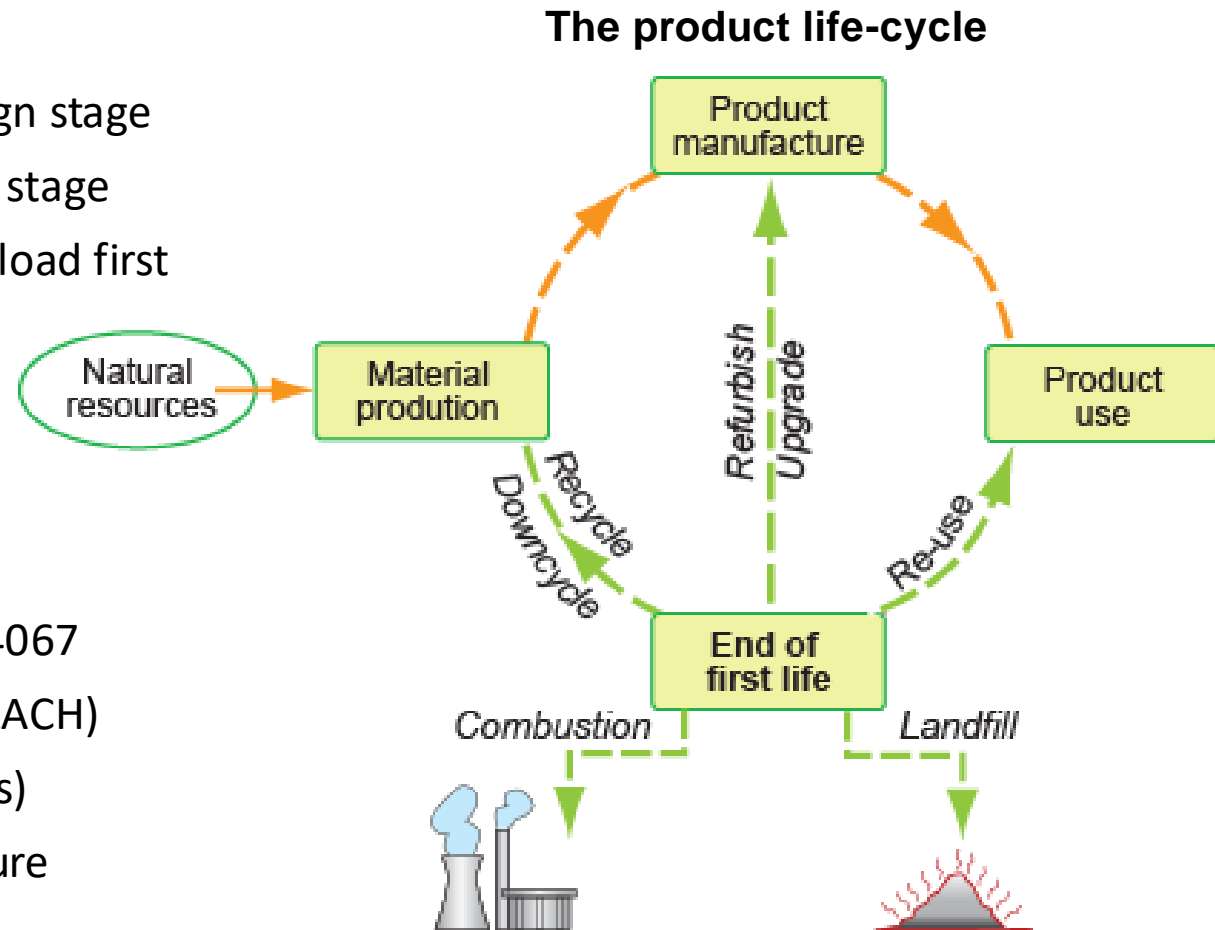
Life-cycles and eco-informed design

Eco-informed design

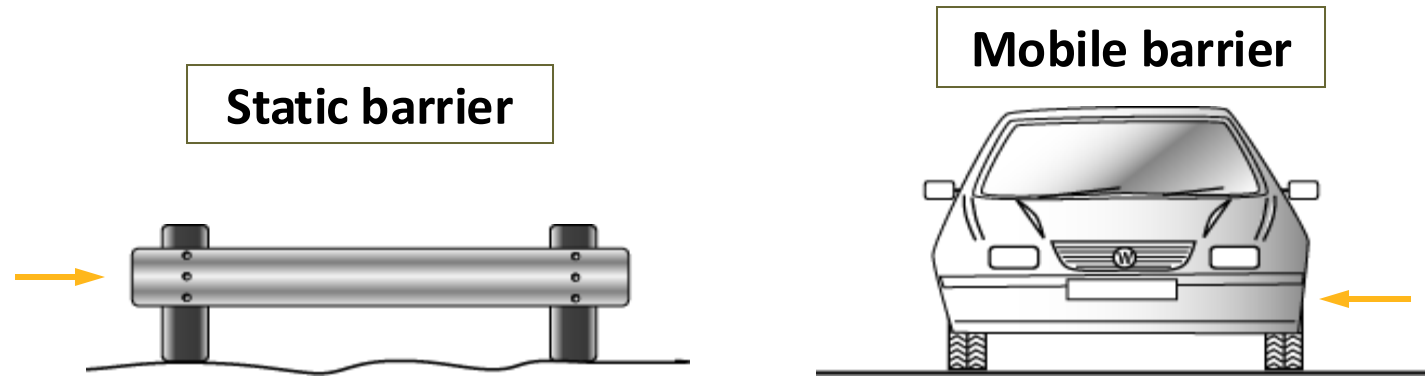
- 80% of eco-impact tied in at design stage
- Build-in eco criteria at the design stage
- Target the largest environmental load first

The drivers for eco-design

- Focus on carbon footprint, ISO 14067
- Legislation (Carbon taxes, EuP, REACH)
- Incentives (Subsidies, concessions)
- Urge for “responsible” manufacture
- Doing more with less = \$\$\$

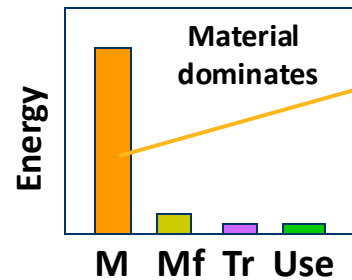


Materials for crash barriers – two important strategies

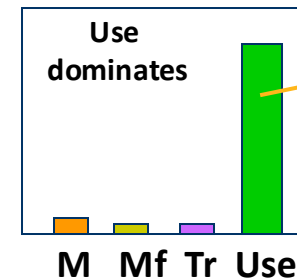


Function: *Absorb impact, transmit load to energy-absorbing units or supports*

Dominant phase of life:



Minimize embodied energy



Minimize mass

Criterion:

Bending strength per unit embodied energy

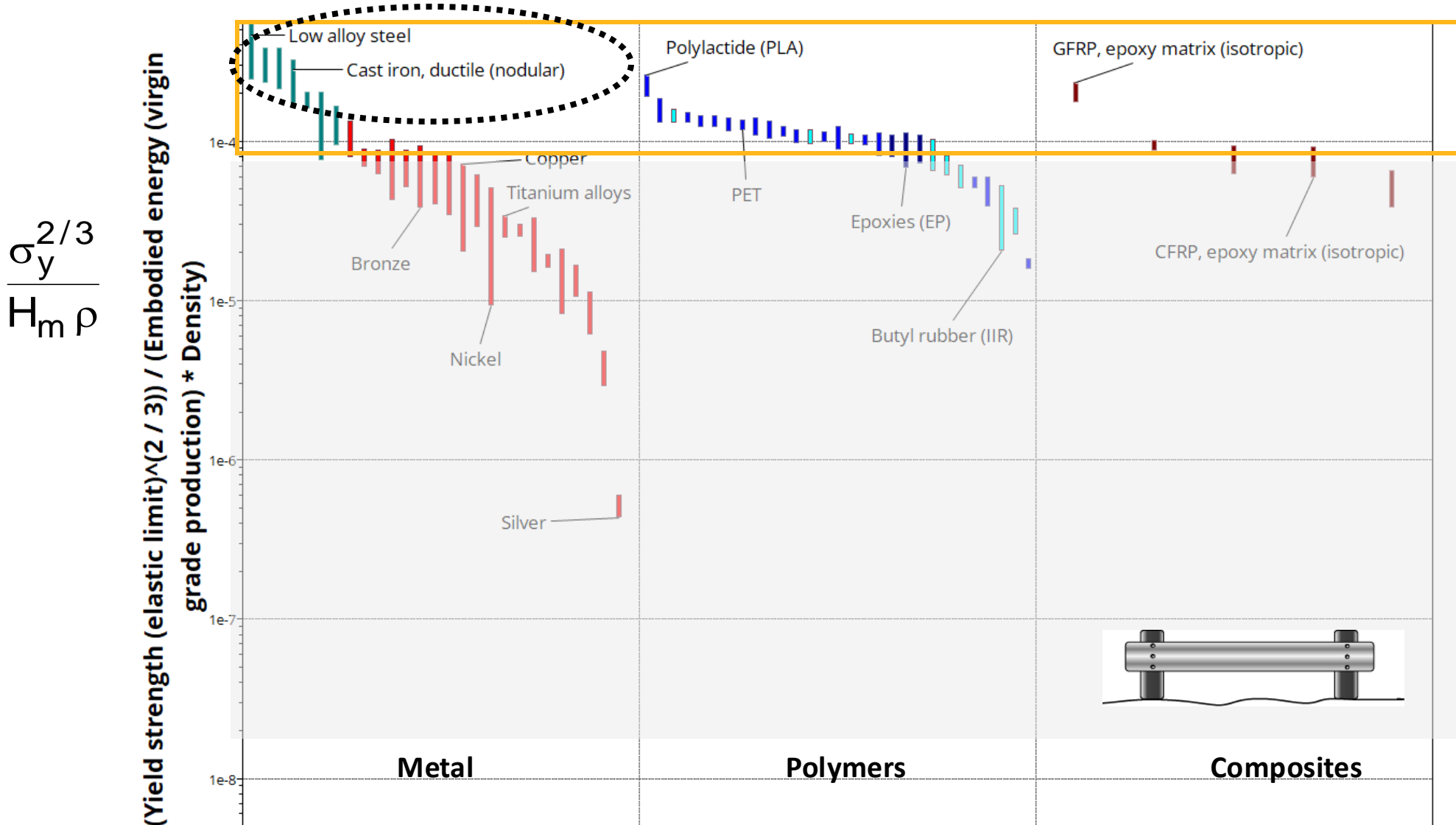
Bending strength per unit mass

Performance Index:

$$\frac{\sigma_y^{2/3}}{H_m \rho}$$

$$\frac{\sigma_y^{2/3}}{\rho}$$

Static barrier: the Performance Index directly as bar chart

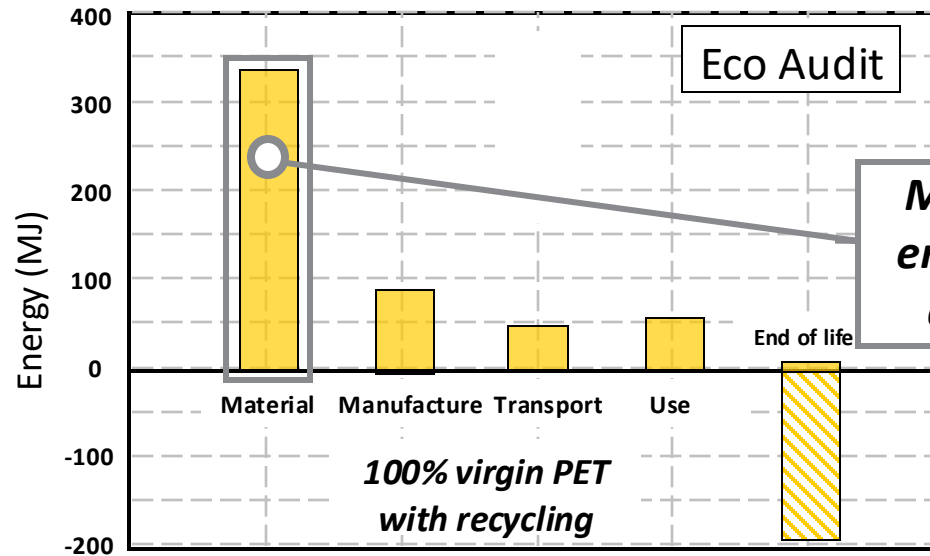


Selected materials: *Steels, Cast irons*

Mobile barrier: the Performance Index directly as bar chart



Eco-selection for a fizzy drink bottle



Material
dominates



Minimize embodied energy

Translation

Design brief

Improve green credentials of bottle



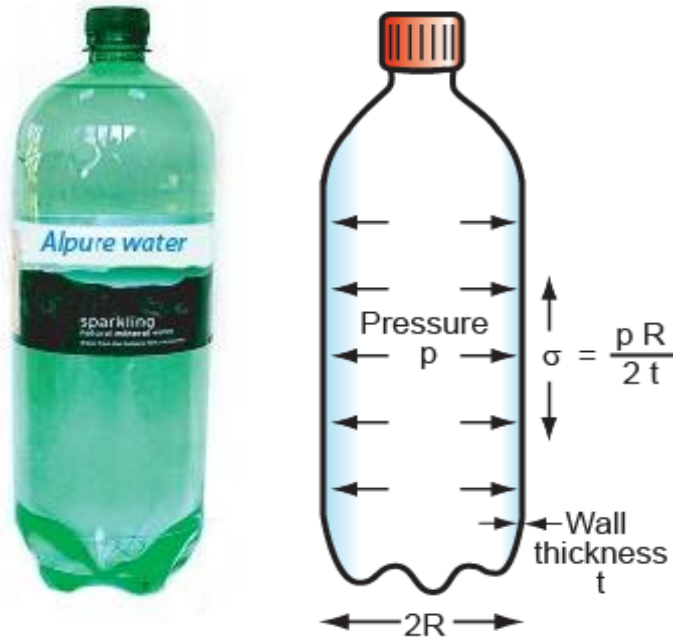
Constraints

- Able to be molded
- Transparent / translucent
- Able to contain pressure

Objectives

- Minimize embodied energy of bottle
- Minimize material cost of bottle

Modelling the bottle



R = Bottle radius
 t = Thickness of bottle wall
 p = Internal pressure
 σ_y = Yield strength of material
 ρ = Density of material
 H_m = Embodied energy of material/kg
 E = Embodied energy/m² of wall
 C_m = Material cost per kg

Cylindrical pressure vessel

- Circumferential stress $\sigma = \frac{pR}{t} < \sigma_y$
 - Embodied energy per unit area of wall
- $$E = t H_m \rho = pR \frac{H_m \rho}{\sigma_y}$$
- Embodied energy / kg of material*
- Find material with lowest energy, seek largest

$$\frac{\sigma_y}{H_m \rho}$$

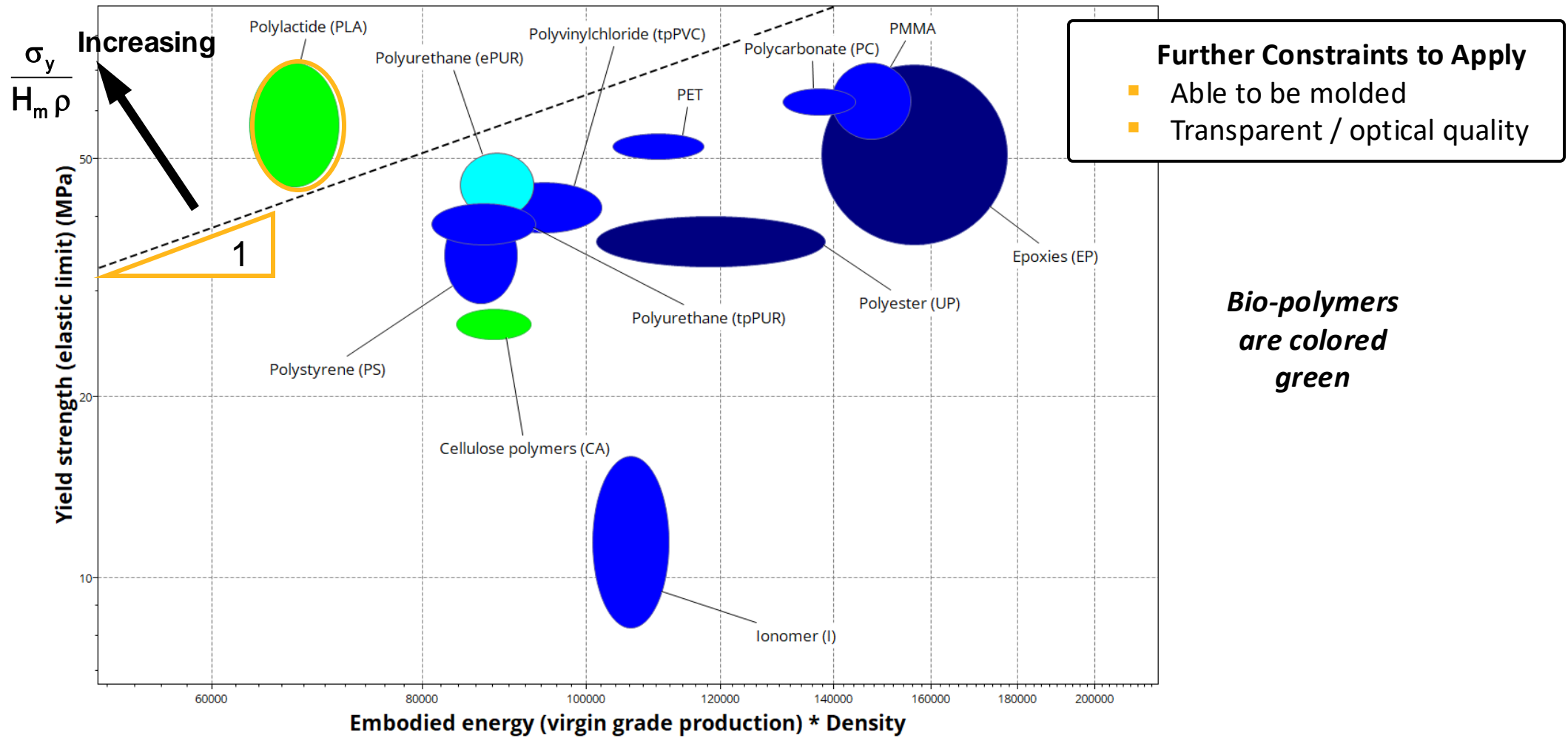
- Find material with lowest cost, seek largest

$$\frac{\sigma_y}{C_m \rho}$$

Price / kg of material

Selection to minimize embodied energy

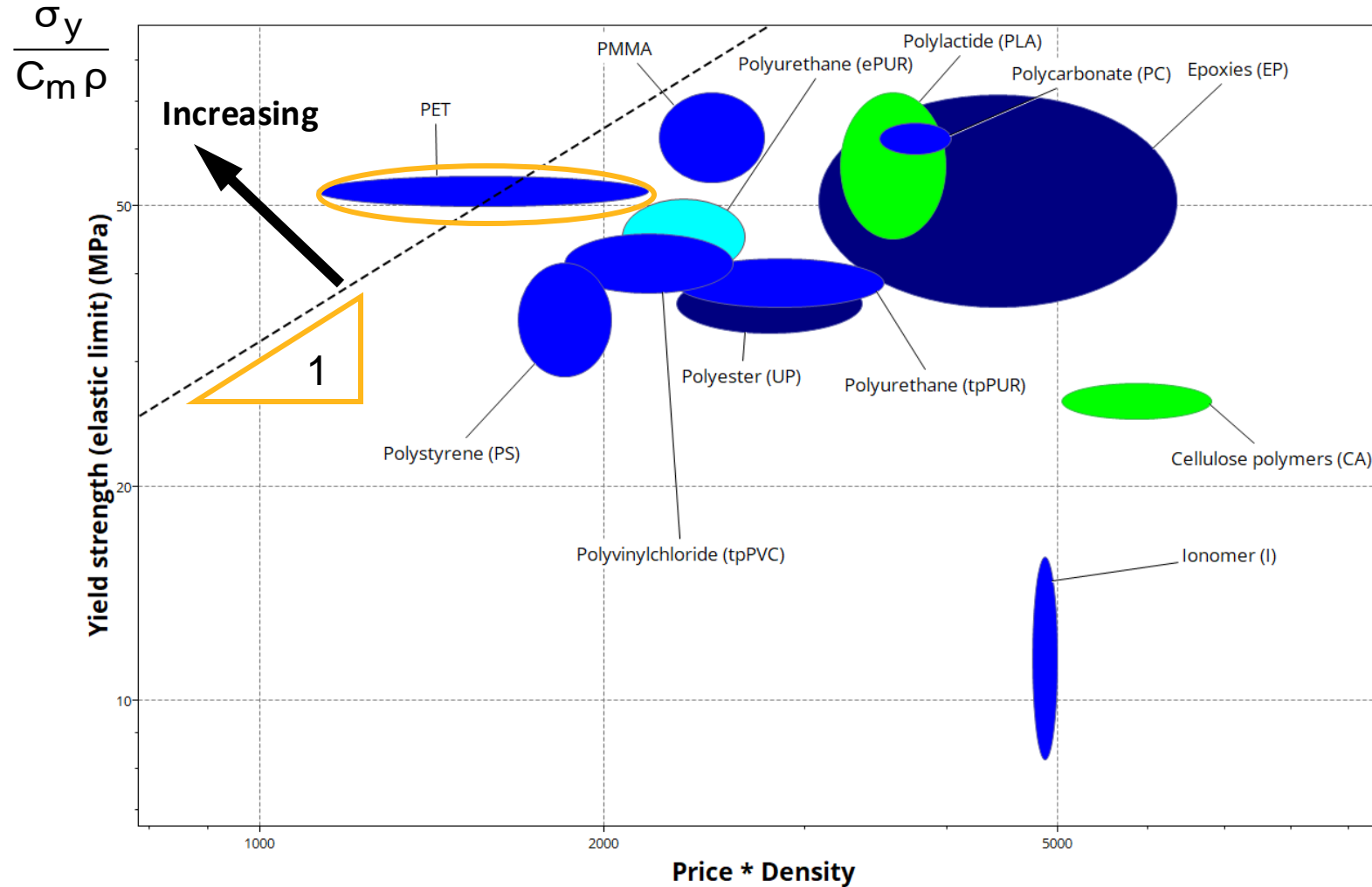
First apply constraints, then use index to optimize choice



PLA meets the constraints at lowest embodied energy

Selection to minimize cost

Can't ignore cost

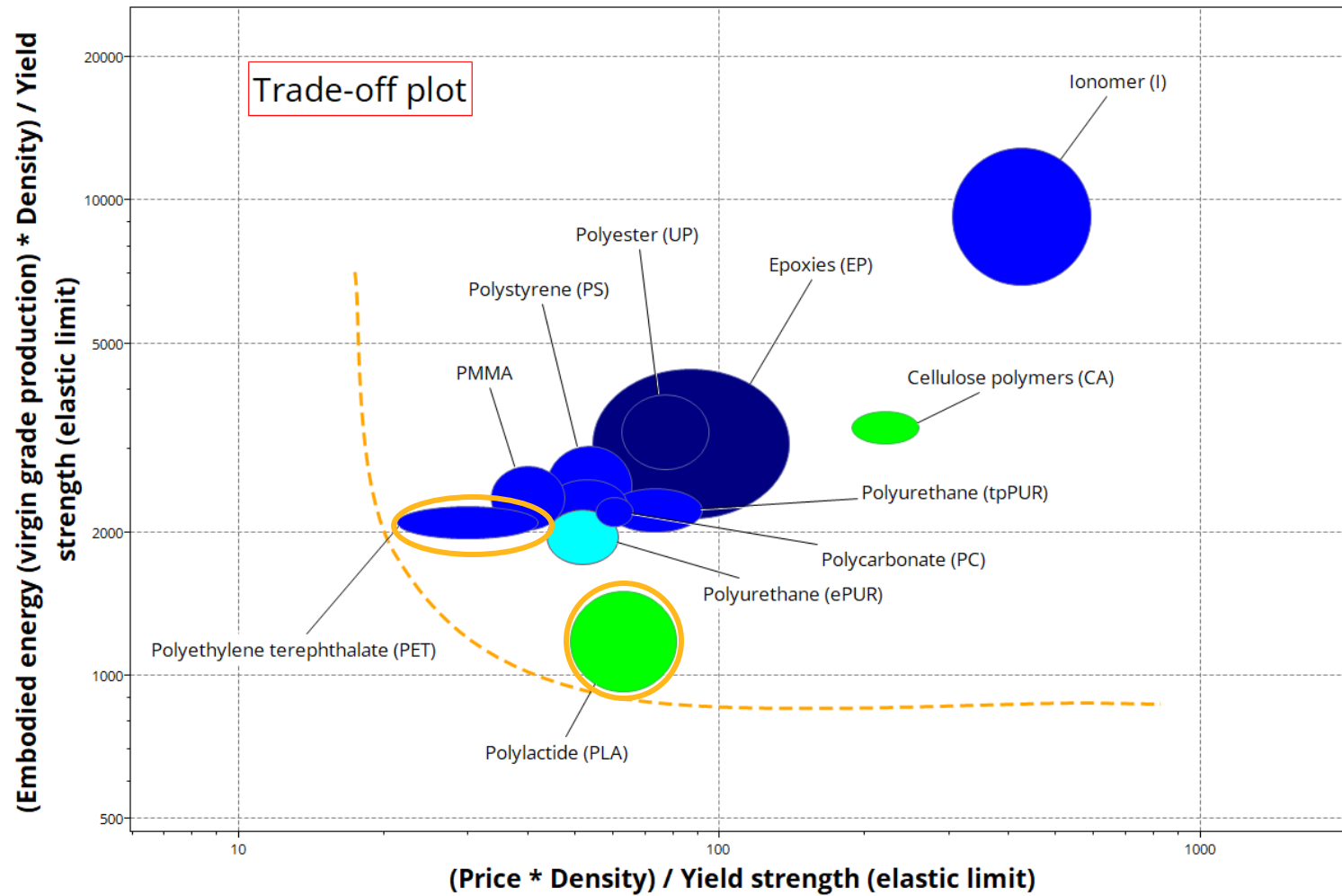


Bio-polymers are colored green

PET meets the constraints at lowest cost

Trade-off plot

Minimizing both embodied energy and cost

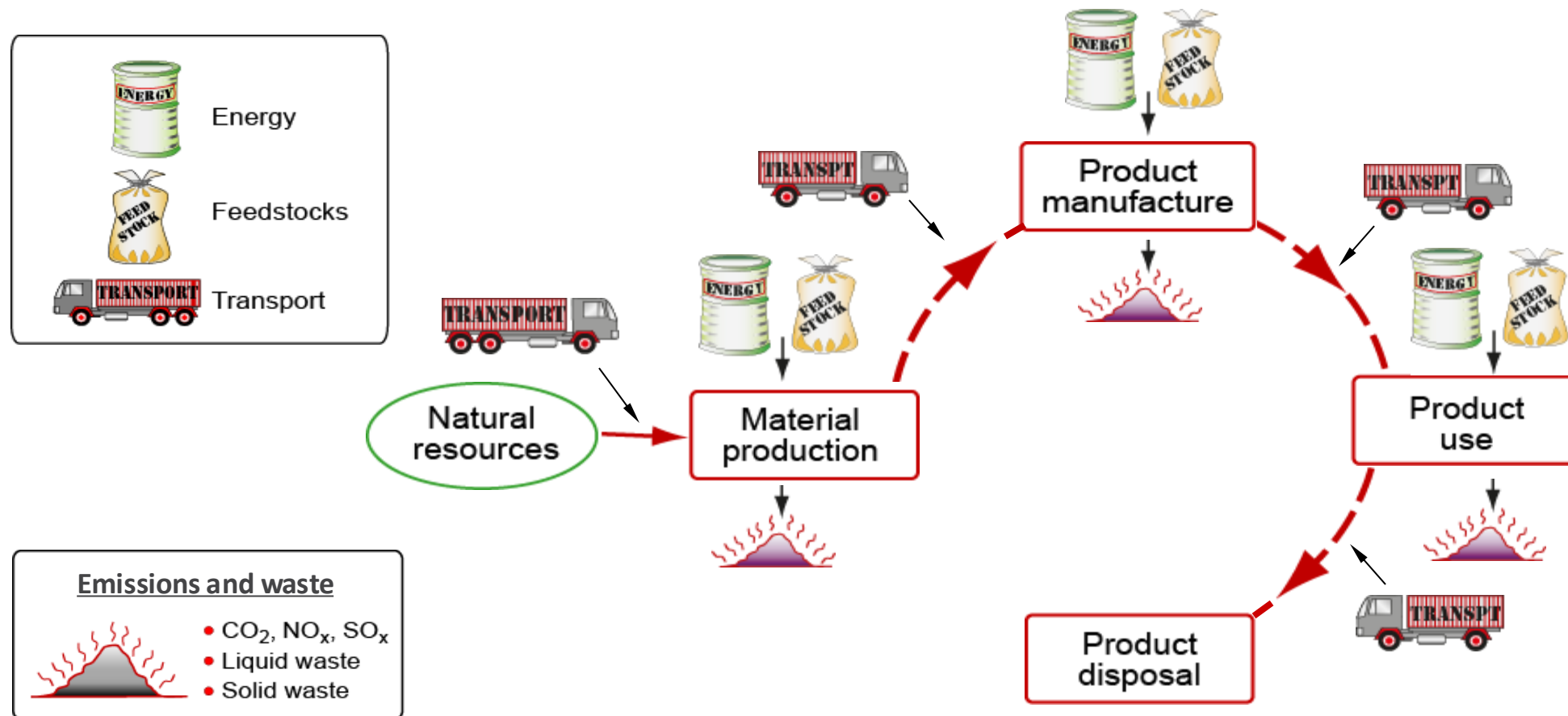


Bio-polymers are colored green

In a trade-off plot, the properties on the axes are to be minimized.

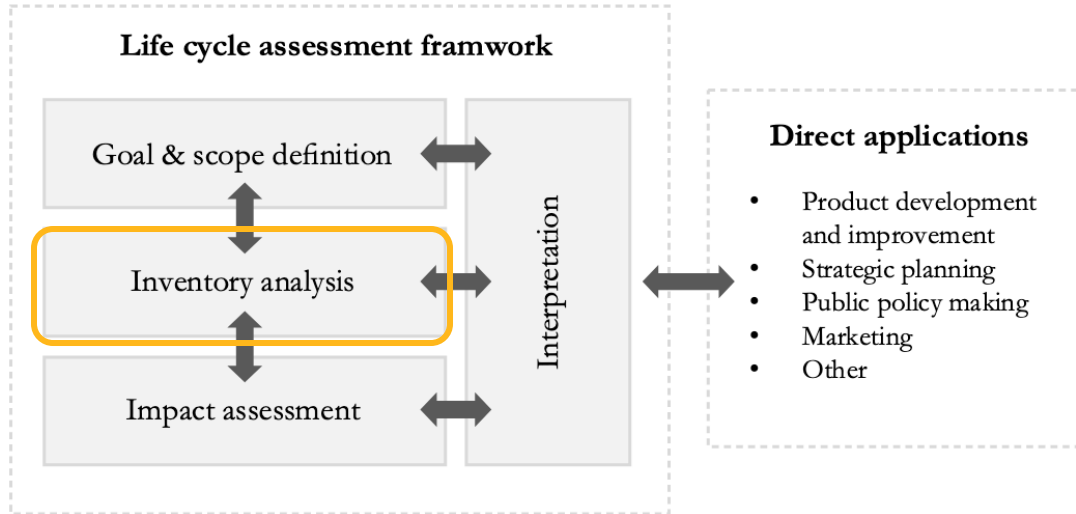
If cost/energy priority not established, both are good candidates

The product life-cycle in detail – 4 phases in first life (cradle-grave)



Life cycle assessment (LCA)

ISO 14040 series, International Standard



Simplified Life-Cycle Inventory (LCI) with Eco Audit

- Full LCA is **expensive**, and requires great **detail and experience** – and even then is subject to uncertainty
- How can a designer use these data?

Typical LCA output

Aluminum cans, per 1000 units

Resource consumption

- Bauxite 59 kg
- Oil fuels 148 MJ
- Electricity 1572 MJ
- Energy in feedstock 512 MJ
- Water use 1149 kg

Emissions inventory

- Emissions: CO₂ 211 kg
- Emissions: CO 0.2 kg
- Emissions: NO_x 1.1 kg
- Emissions: SO_x 1.8 kg
- Particulates 2.47 kg

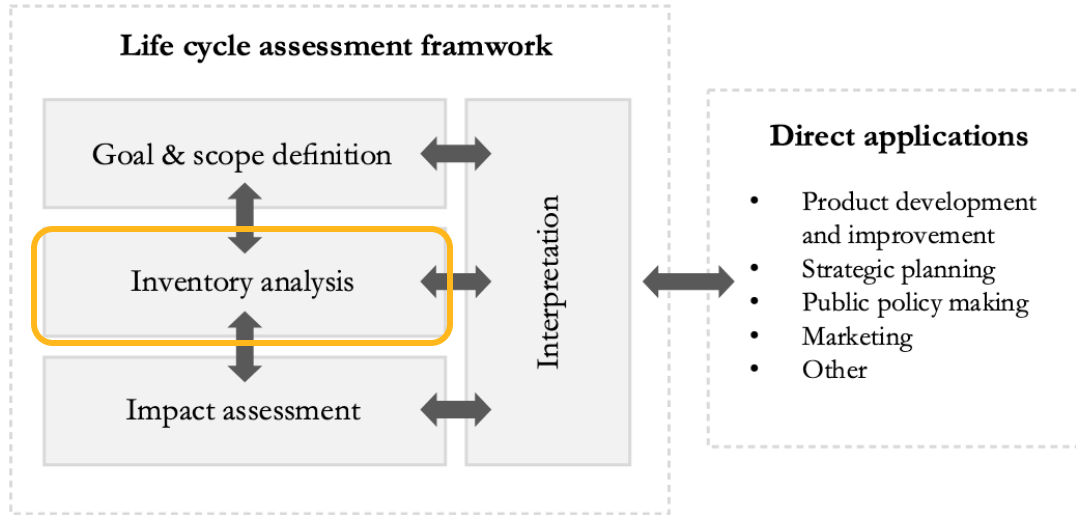
Impact assessment

- Ozone depletion potential 0.2 X 10⁻⁹
- Global warming potential 1.1 X 10⁻⁹
- Acidification potential 0.8 X 10⁻⁹
- Human toxicity potential 0.3 X 10⁻⁹

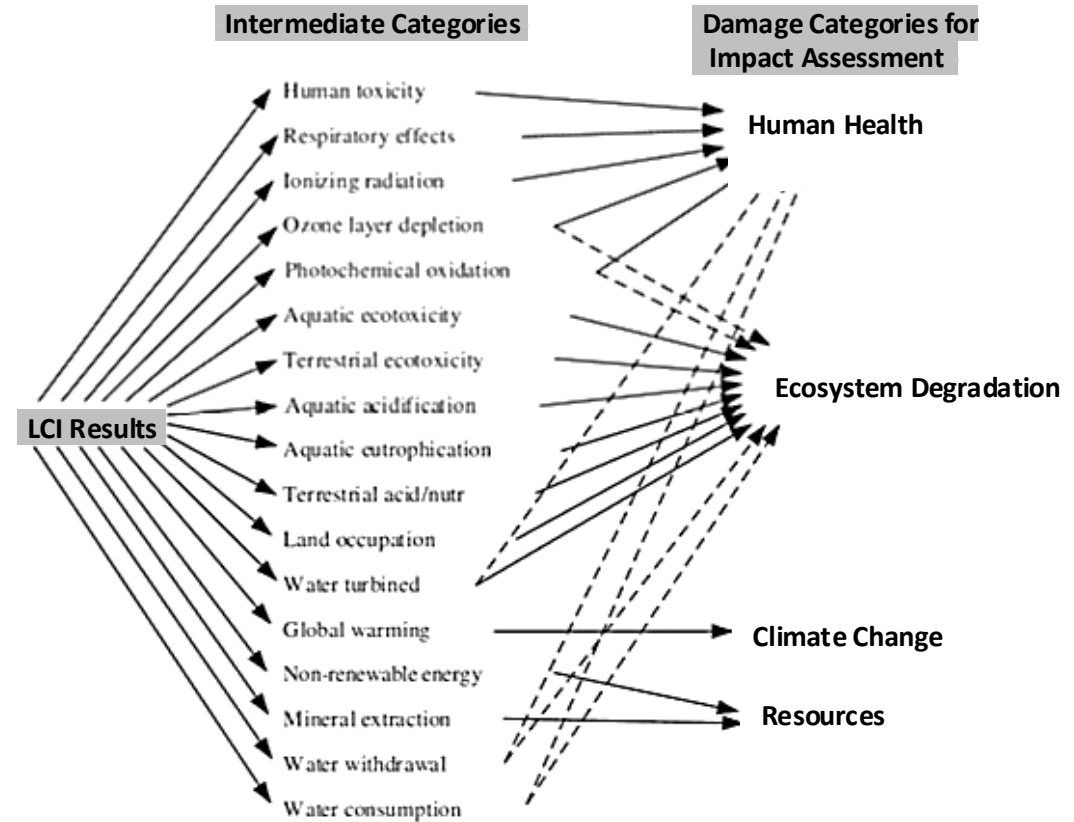
LCA Framework in ISO 14044:2006

Life cycle assessment (LCA) vs Life-cycle Inventory (LCI)

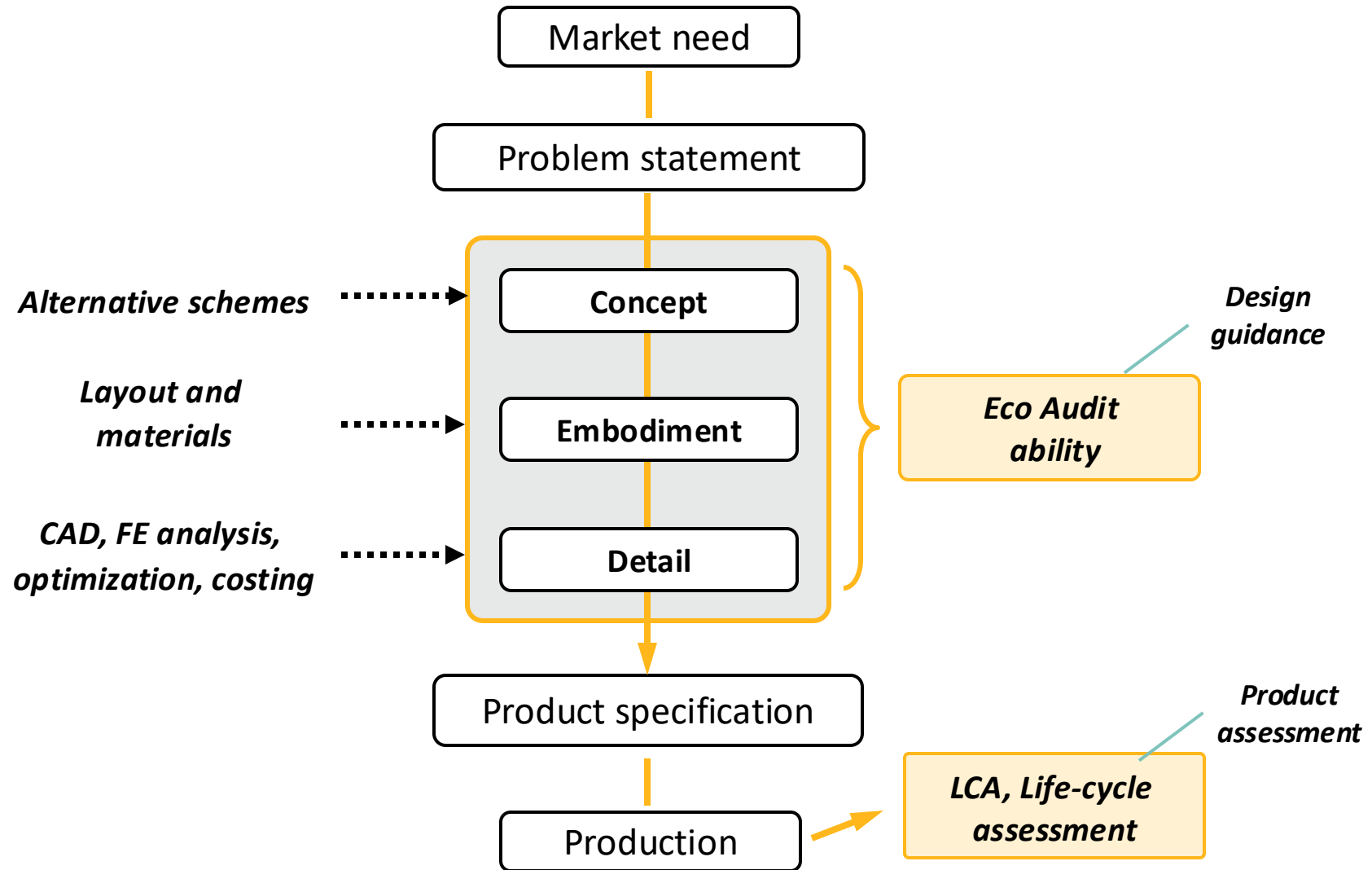
PAS 2050 by the British Standards Institute (BSI)
ISO 14040 series, International Standard



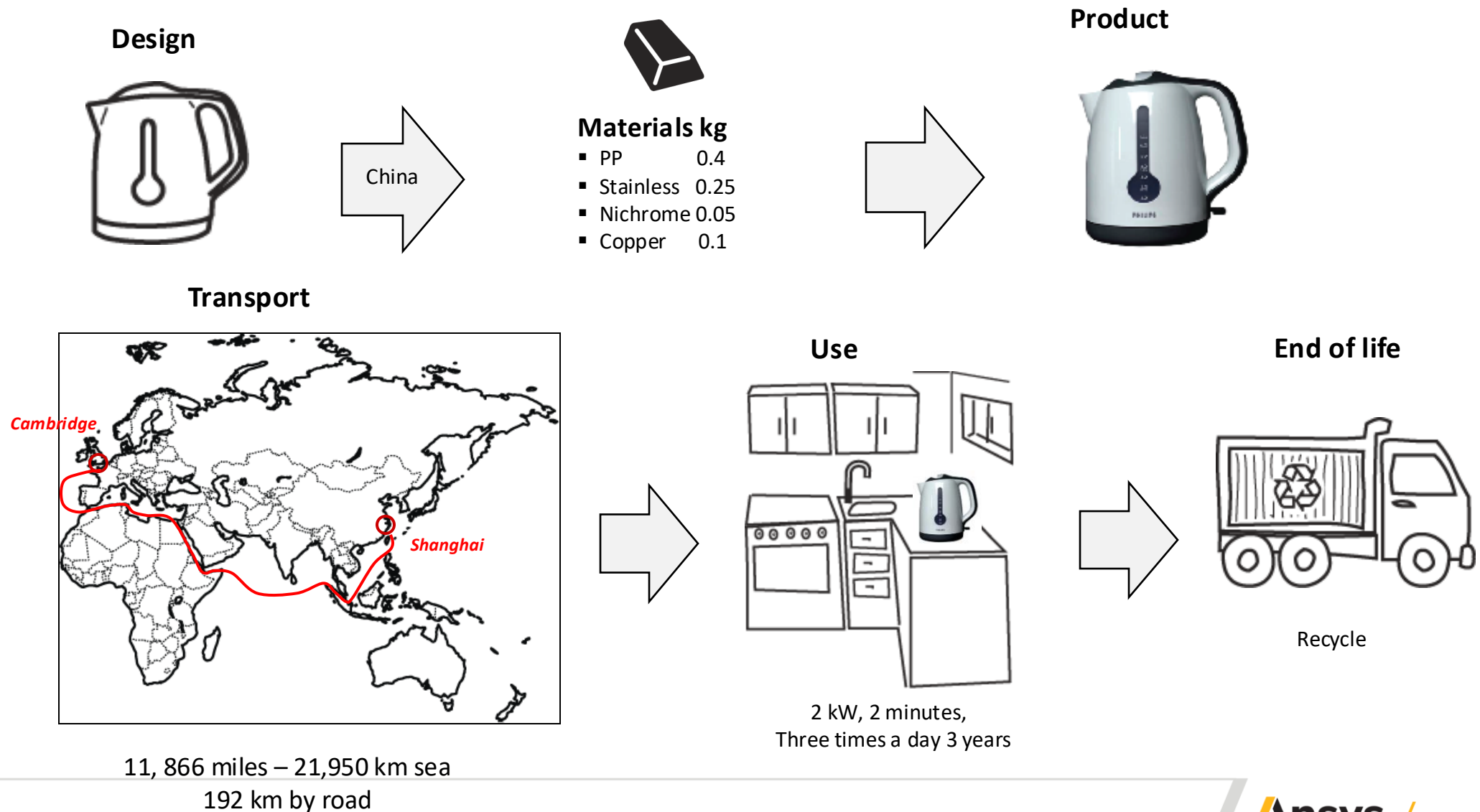
Simplified Life-Cycle Inventory (LCI) with Eco Audit



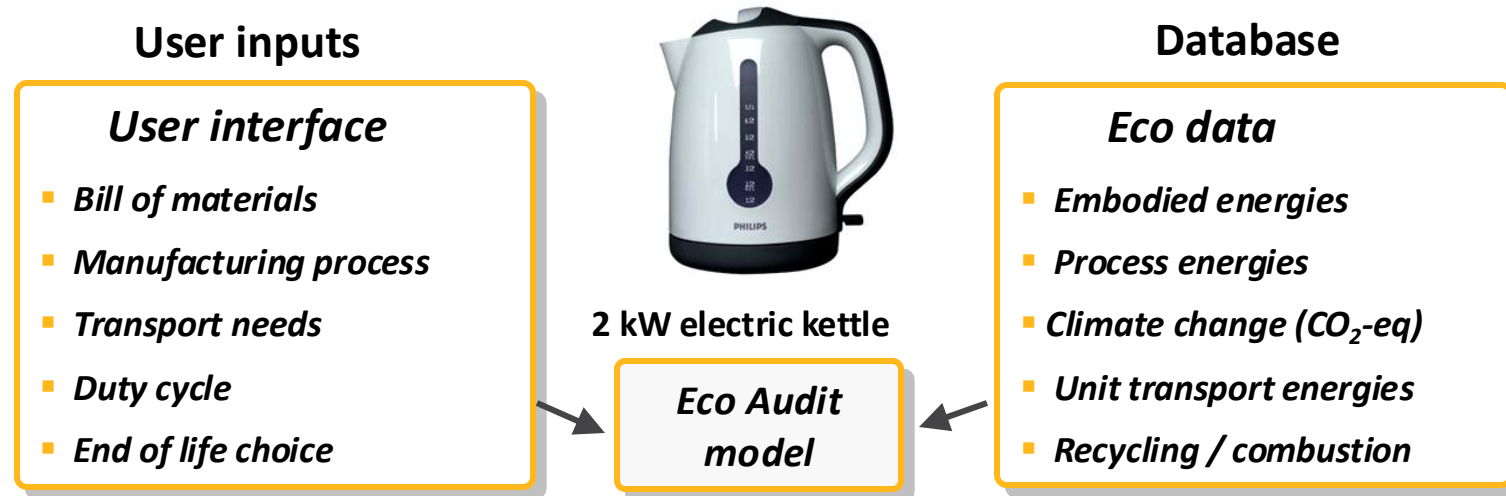
Design guidance vs product assessment



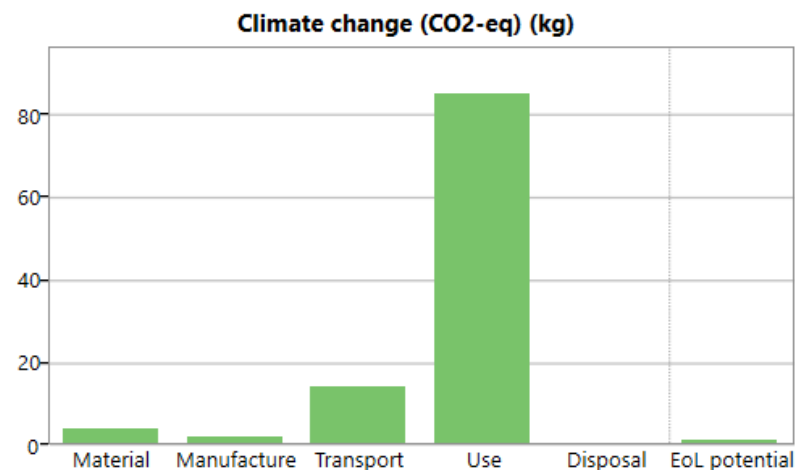
Life-cycle overview – Example: Jug Kettle



Ansys Granta EduPack software Eco Audit Tool



Outputs:



Use is 88%
of life-energy

Full report

- Data
- Criticality
- Hazard

The Eco Audit input interface at Level 2

Eco Audit Project

Product definition | Report

New | Open | Save | Compare with... ← Useful for what-if?

Product information

Name: Electric kettle

Material, manufacture and end of life

How do I use my own materials or processes?

Qty.	Component name	Material	Recycled content	Mass (kg)	Primary process	End of life
1	Kettle body	Polypropylene (PP)	Virgin (0%)	0.86	Polymer molding	Combust
1	Heating element	Nickel-chromium allo...	Virgin (0%)	0.026	Roll forming	Recycle
1	Casting, heating element	Stainless steel	Virgin (0%)	0.09	Casting	Recycle
1	Cable sheath, 1 meter	Natural rubber (NR)	Virgin (0%)	0.06	Polymer molding	Combust
1	Cable core, 1 meter	Copper	Virgin (0%)	0.015	Wire drawing	Recycle
1	Plug body	Phenolics (PF)	Virgin (0%)	0.037	Polymer molding	Combust
1	Plug pins	Brass	Virgin (0%)	0.03	Extrusion, foil rolling	Recycle
1	Packaging, padding	Rigid Polymer Foam (MD)	Virgin (0%)	0.015	Polymer molding	Combust
1	Packaging, box	Paper and cardboard	Virgin (0%)	0.125		Recycle

Transport

Name	Transport type	Distance (km)
Factory to Airport	Truck 7.5-16t, EURO 5	200
SE Asia to UK	Aircraft, long haul, dedicat	1.4e+04
Airport to retailer	Truck 7.5-16t, EURO 5	200

Use

Product life: 3 Years

Country of use: United Kingdom

Static mode Product uses the following energy:

Energy input and output: Electric to thermal

Power rating: 2 kW

Usage: 365 days per year

Usage: 0.15 hours per day

Mobile mode Product is part of or carried in a vehicle:

Fuel and mobility type: Diesel - light goods vehicle

Usage: 21 days per year

Distance: 300 km per day

Report

Summary chart | Detailed report

Image: Note:

**Bill of Materials
(Input or file)**

> 5wt% critical material

- End-of-Life**
- Landfill
 - Combust
 - DOWncycle
 - Recycle
 - Re-manufacture
 - Reuse
 - None

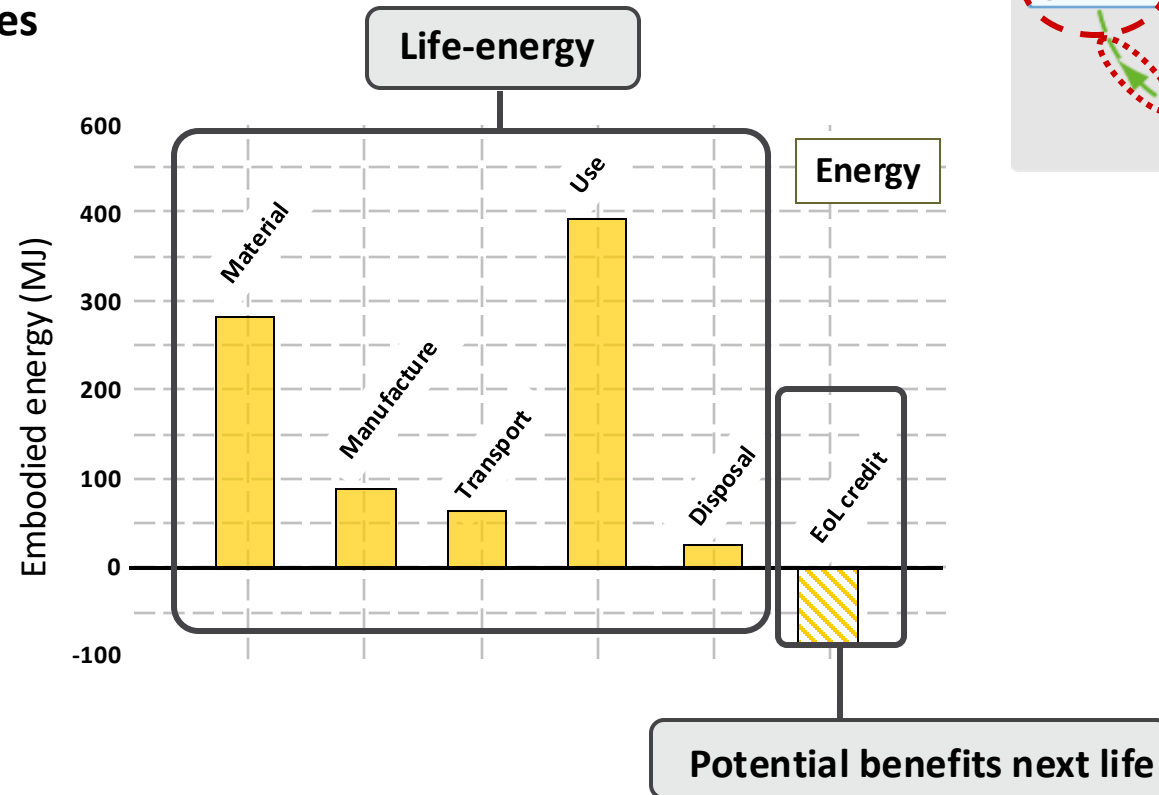
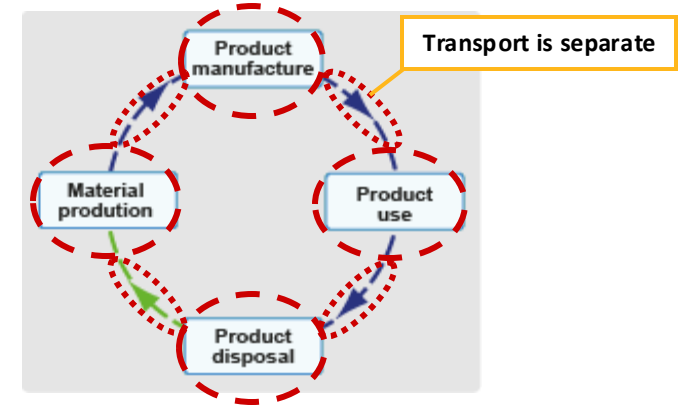
**Help at
each step**

**Output data
(Detailed info)**

Eco Audit output for design

Need: Fast **Eco Audit** with sufficient precision to guide decision-making

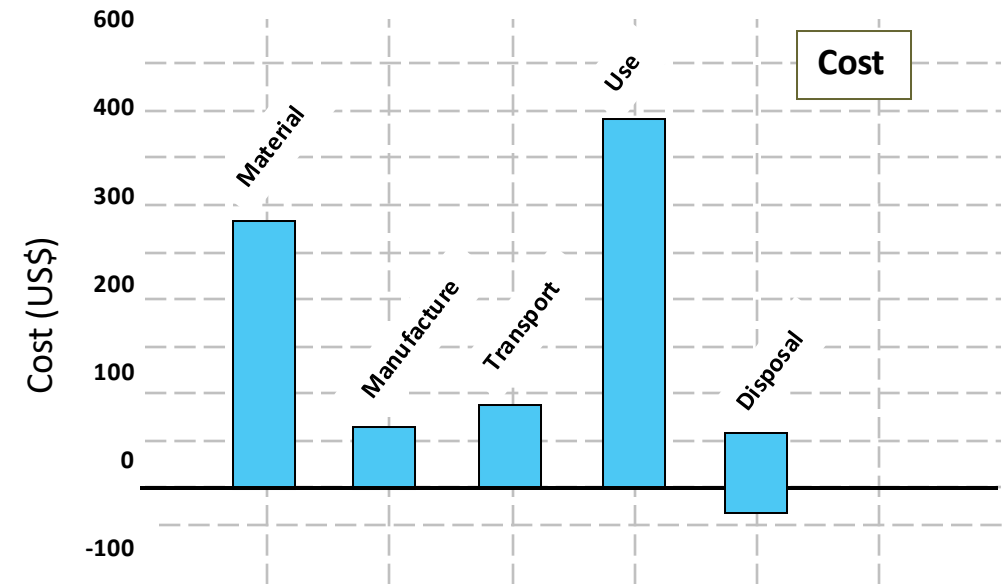
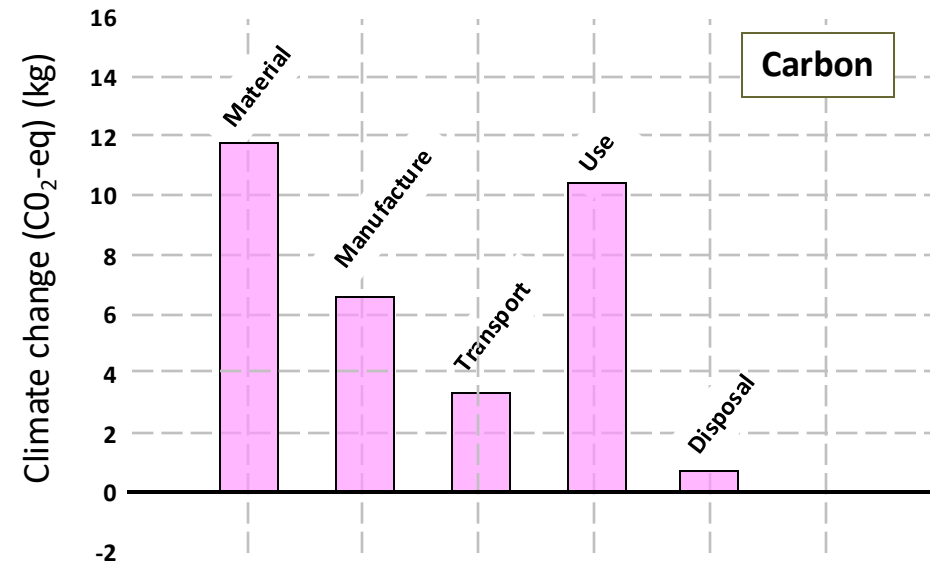
- 1 resource – *Embodied energy [MJ/kg]*
- 1 emission – *Climate change (CO₂-eq) [kg/kg]*
- Distinguish life-phases
- Audit: Energy



Eco Audit output for design

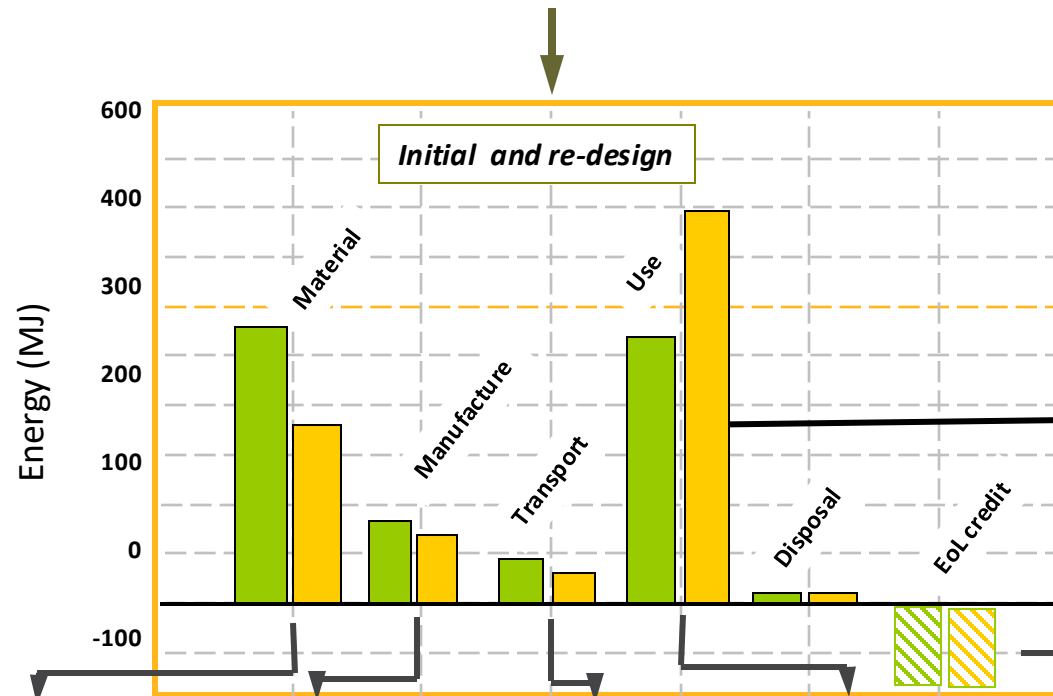
Need: Fast **Eco Audit** with sufficient precision to guide decision-making

- 1 resource – *Embodied energy [MJ/kg]*
- 1 emission – *Climate change (CO₂-eq) [kg/kg]*
- Distinguish life-phases
- Audit: Energy, CO₂ or Cost



Eco-informed selection: the strategy

The steps



- When we did “what if’s” we were guessing
- Can we do better?
Be systematic?

Click on bar for advice

- Use Eco Audit or other tools to explore design improvements
- Apply the selection methodology

Material
Minimize:

- material in part
- embodied energy
- CO₂/kg

Manufacture
Minimize:

- process energy
- CO₂/kg

Transport
Minimize:

- mass
- distance
- transport type

Use
Minimize:

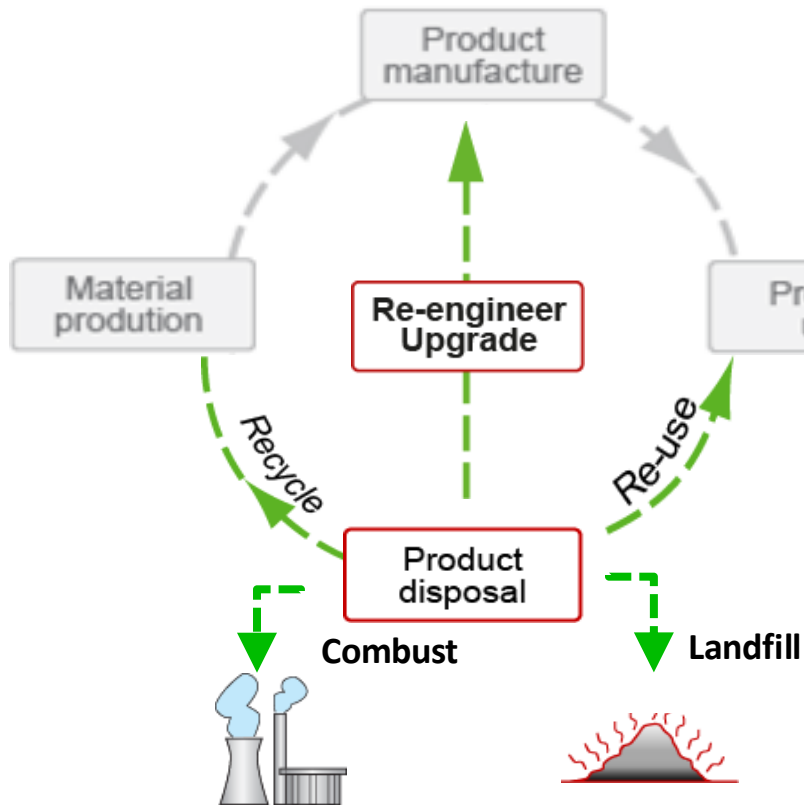
- mass
- thermal loss
- electrical loss

End of Life
Select:

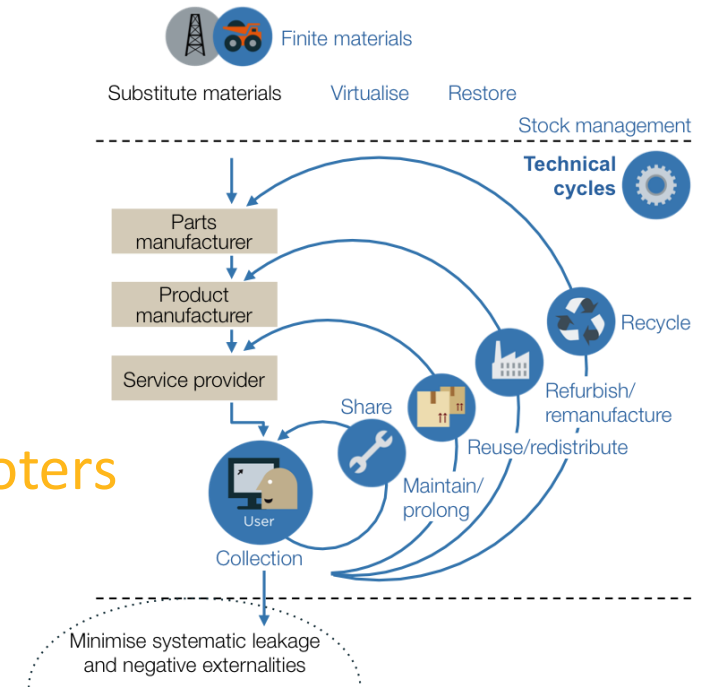
- recyclable materials
- non-toxic materials

A closer look at Product disposal and End-of-life – phase 4

The product life-cycle

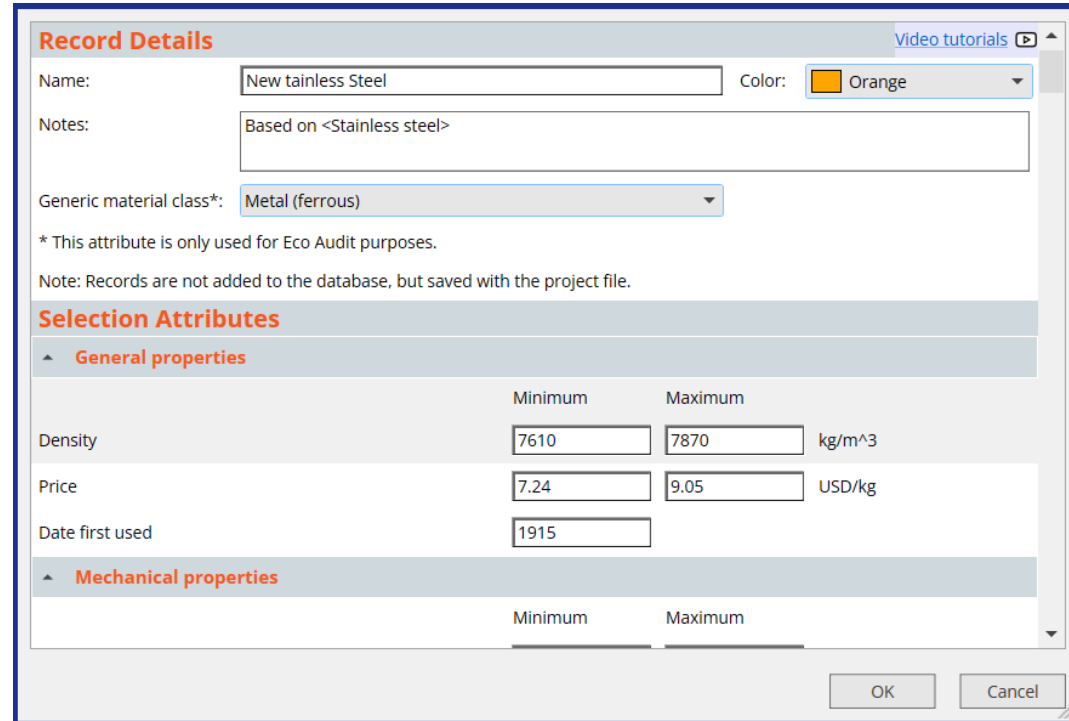
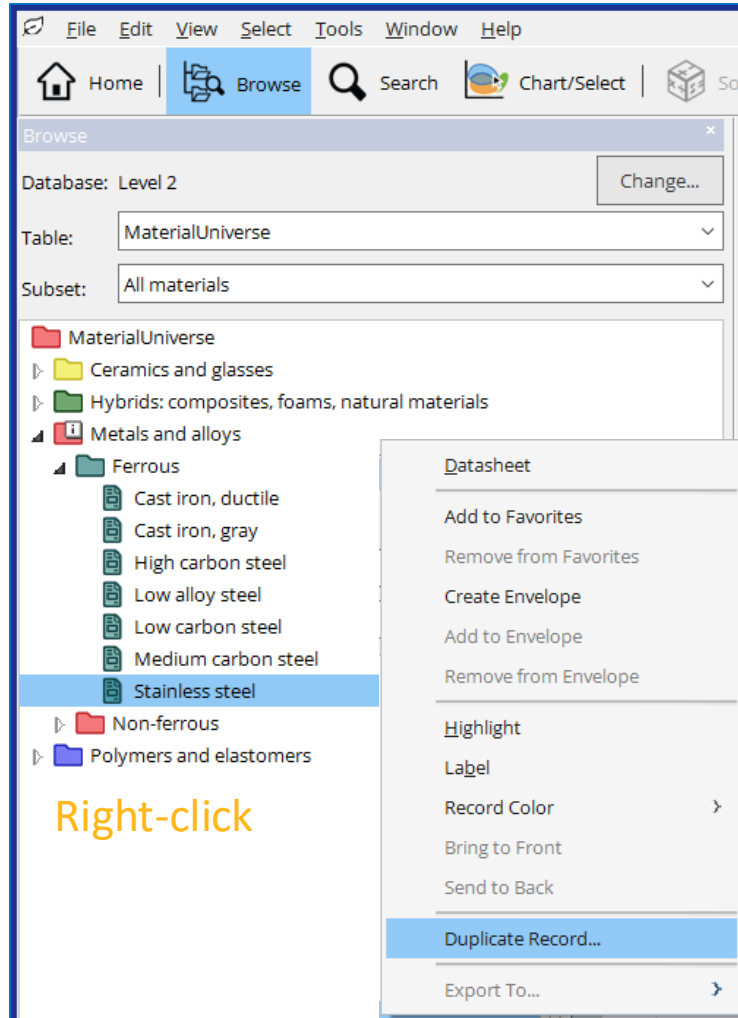


- Landfill (not good – to avoid)
- Combust (energy recovered but material lost)
- Downcycle (non-functional)
- Recycle (functional recycling)
- Re-engineer/Upgrade (repair, modernize)
- Re-use (second hand, inherit)
- Sharing (carpool, electric scooters)
- Circularity – `next life:



SOURCE: Adopted from original by the Ellen MacArthur Foundation

Add your own records, based on existing ones, to Eco Audit



Both custom Materials and Processes can be included in Eco Audit

The screenshot displays the 'Eco Audit Project' software interface. The main window shows a table of components for an 'Electric kettle'. A 'Browse' dialog box is open, allowing the user to select a material and a primary process for a component.

Product information
Name: Electric kettle

Material, manufacture and end of life
[How do I use my own materials or processes?](#)

Qty.	Component name	Material	Recycled content	Mass (kg)	Primary process	End of life
1	Kettle body	Polypropylene (PP)	Virgin (0%)	0.86	Polymer molding	Combust
1	Heating element	Nickel-chromium allo...	Virgin (0%)	0.026	Roll forming	Recycle
1	Casting		Virgin (0%)	0.09	Casting	Recycle
1	Cable st...		Virgin (0%)	0.06		Combust
1	Cable co...		Virgin (0%)	0.015		Recycle
1	Plug bo...		Virgin (0%)	0.037		Combust
1	Plug pin...		Virgin (0%)	0.03		Recycle
1	Packagi...		Virgin (0%)	0.015		Combust
1	Packagi...		Virgin (0%)	0.125		Recycle

Browse

- MaterialUniverse
 - Ceramics and glasses
 - Electrical components (Eco Audit only)
 - Hybrids: composites, foams, natural materials
 - Metals and alloys
 - Ferrous
 - Cast iron, ductile
 - Cast iron, gray
 - High carbon steel
 - Low alloy steel
 - Low carbon steel
 - Medium carbon steel
 - Stainless steel
 - Non-ferrous
 - Polymers and elastomers
 - My records

Primary process dropdown: Casting, Roll forming, Forging, Extrusion, foil rolling, Wire drawing, Metal powder forming, Vaporization, Add custom process...

Transport

Name	(km)
Factory to Airp...	
SE Asia to UK	
Airport to retailer	Truck 7.5-16t, EURO 5 200

Glass bottle with cap: Step 1. Material and process energy / CO₂

Component name	Material	Process	Mass (kg)	End of life
Component 1	Aluminum alloys	Forging/Rolling	0.002	Recycle

Granta EduPack materials tree

- MaterialUniverse
 - Ceramics and glasses
 - Hybrids: composites, foams, natural materials
 - Metals and alloys
 - Ferrous
 - Non-ferrous
 - Aluminum and alloys
 - Age-hardening wrought Al-alloys
 - Cast Al-alloys
 - Non age-hardening wrought Al-alloys
 - Copper and alloys
 - Gold
 - Lead and alloys
 - Magnesium and alloys
 - Nickel and alloys
 - Silver
 - Tin
 - Titanium and alloys
 - Tungsten alloys
 - Zinc and alloys
 - Polymers and elastomers
 - Elastomers
 - Polymers
 - Thermoplastics
 - Acrylonitrile butadiene styrene (ABS)
 - Cellulose polymers (CA)
 - Ionomer (I)

- Casting
- Forging / rolling
- Extrusion
- Wire drawing
- Powder forming
- Vapor methods

- Landfill
- Downcycle
- Recycle
- Re-manufacture
- Reuse
- None

End of life options

Glass bottle with cap: Step 2. Material and process energy / CO₂

Component name	Material	Process	Mass (kg)	End of life
Component 1	Aluminum alloys	Rolling	0.002	Recycle
Component 2	Glass	Glass molding	0.45	Reuse

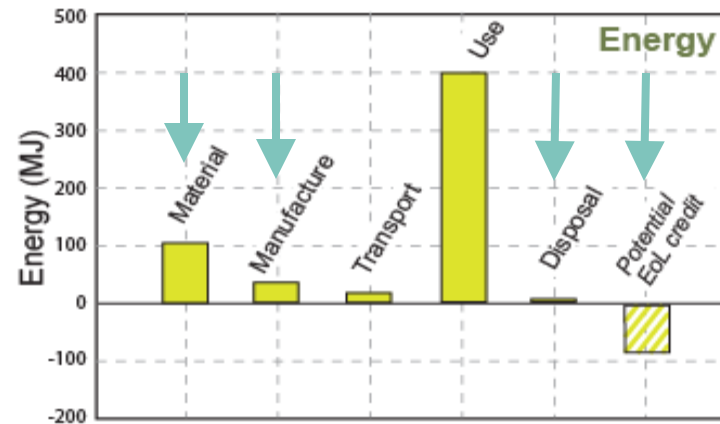
Total embodied energy

Total process energy

Total mass

Total end of life energy

- Don't forget to put the number of each component



Step 3. Transport

- Eco Audit assumes optimal (fully) loaded transports

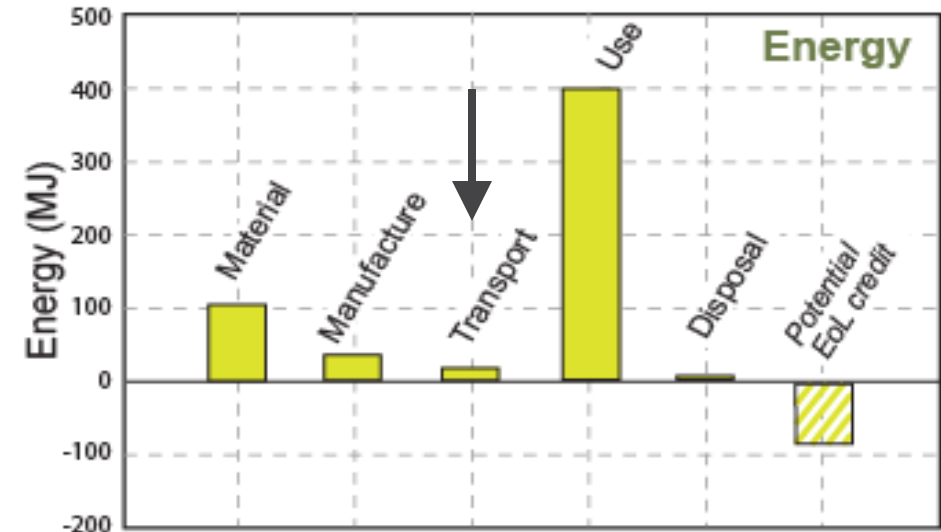
Transport stage	Transport type	Distance (km)
Stage 1	Truck 3.5-7.5t, EURO 5	350
Stage 2	Sea, bulk carrier	12 000

Transport energy

Transport CO₂ Eq

- Light commercial vehicle
- Truck 3.5-7.5t, EURO 3
- Truck 3.5-7.5t, EURO 4
- Truck 3.5-7.5t, EURO 5**
- Truck 3.5-7.5t, EURO 6
- Truck 7.5-16t, EURO 3
- Truck 7.5-16t, EURO 4
- Truck 7.5-16t, EURO 5
- Truck 7.5-16t, EURO 6
- Truck 16-32t, EURO 3
- Truck 16-32t, EURO 4
- Truck 16-32t, EURO 5
- Truck 16-32t, EURO 6
- Truck >32t, EURO 3

Table of transport types:
 MJ / tonne.km
 CO₂ / tonne.km



Step 4. Use phase – static mode

Energy input and output

Electric to mechanical

Power rating

1.2 kW

Usage

365 days per year

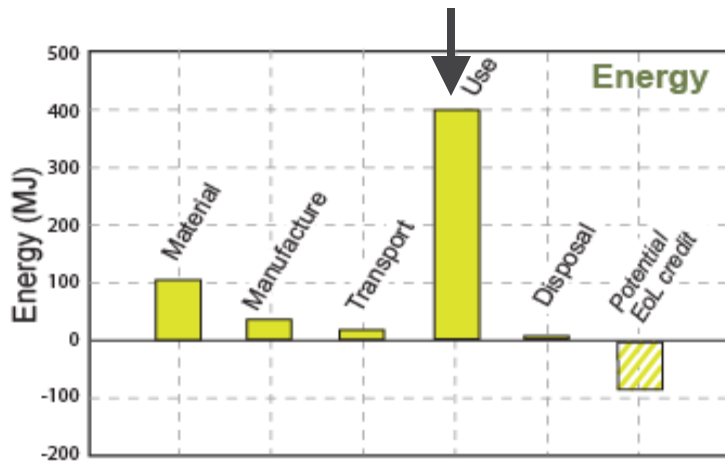
Usage

0.5 hours per day

Total energy or CO2-eq for use

Energy input and output

- Electric to thermal
- Electric to mechanical (electric motors)**
- Electric to chemical (lead acid battery)
- Electric to chemical (advanced battery)
- Electric to em radiation (incandescent lamp)
- Electric to em radiation (LED)
-
- Fossil fuel to thermal, enclosed system
- Fossil fuel to thermal, vented system
- Fossil fuel to electric
- Fossil fuel to mechanical, internal combustion
- Fossil fuel to mechanical, steam turbine
- Fossil fuel to mechanical, gas turbine
-
- Light to electric (solar cell)



- A fridge has electric to mechanical energy losses, due to the compressor

New example. Bottled water in PET (100 units)



- 1 litre PET bottle with PP cap
- Blow molded
- Filled in France, transported 550 km to UK
- Refrigerated for 2 days, then drunk

Product name: **PET bottle**

New **Open** **Save** **Compare with...**

Number	Name	Material	Process	Mass (kg)	End of life
100	Bottles	PET	Molding	0.04	Recycle
100	Caps	Polypropylene	Molding	0.001	Landfill
100	Water		1.0		

Transport

Stage 1 **Truck 7.5-16t, EURO 5** **550 km**

Use - refrigeration

Electric to mechanical **0.12 kW** **2 days** **24 hrs/day**

Survey charts **Full report**

Change the materials

- 1 litre **glass bottle** with **aluminum cap**
- **Glass molded**
- Filled in France, transported 550 km to UK
- Refrigerated for 2 days, then drunk



Copy of current project
New project
Saved project

Product name: *Glass bottle*

New

Open

Save

Compare with... ▾

Number	Name	Material	Process	Mass (kg)	End of life
100	Bottles	Soda glass ▾	Glass molding ▾	0.45	Recycle ▾
100	Caps	Aluminum ▾	Forging/Rolling ▾	0.002	Landfill ▾
100	Water	▾	1.0 ▾		▾

Transport

Stage 1

Truck 7.5-16t, EURO 5 ▾

550 km

Use - refrigeration

Electric to mechanical

0.12 kW ▾

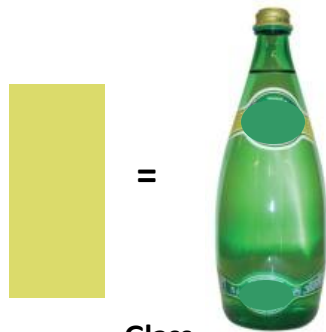
2 days

24 hrs/day

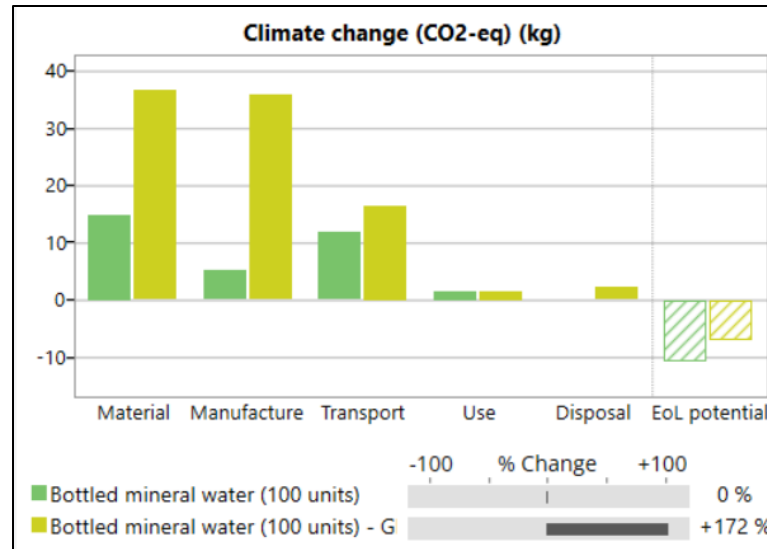
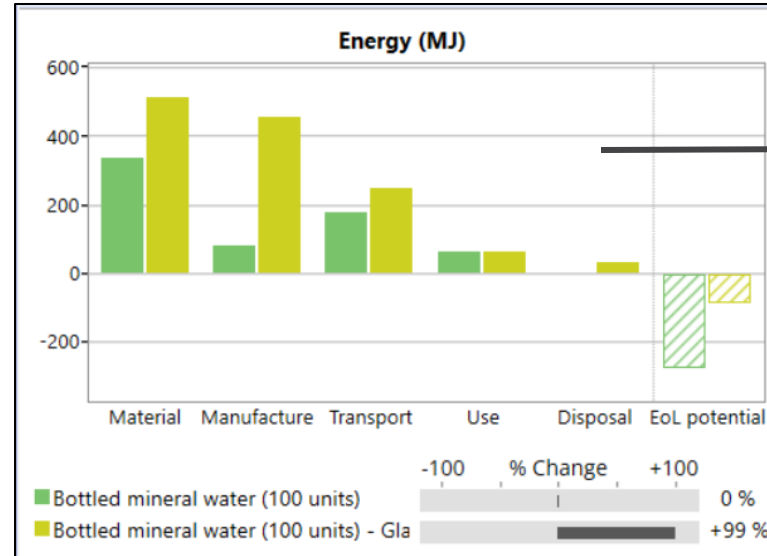
Actions and comparisons



Virgin PET



Glass



The fast comparison allows design decisions on-the-fly

Reducing impact

- Actions**
- Use as large a 'recycled content' in the material as possible.

- Can explore:**
- Material choice
 - Recycle content
 - Transport mode
 - Transport distance
 - Use pattern
 - Electric energy mix
 - End of life choice

Many projects are available as project files.

The Enhanced Eco Audit tool

Home | Browse | Search | Chart/Select | Solver | **Eco Audit** | Synthesizer | Learn | Tools | Settings | Help

Home | Electric kettle

Eco Audit Project

Product definition | Report

New | Open | Save | Compare with...

Product information

Name: Electric kettle

Include cost analysis **Cost Audit**

Country of manufacture: Asia

Package dimensions: H: 0.4 m | W: 0.3 m | D: 0.3 m

Material, manufacture and end of life

How do I use my own materials or processes?

Components

Qty.	Component name	Material	Recycled content	Mass (kg)	Primary process	Length (m)	Secondary process	% removed	End of life	% recovered
1	Kettle body	PP (random copolym...)	Virgin (0%)	0.86	Polymer molding (injection, blow)	Not Required		0	Combust	20
1	Heating element	Nickel-chromium allo...	Typical %	0.026	Wire drawing	0	Cutting and trimming	5	Recycle	20
1	Casting, heating element	Stainless steel, auste...	Virgin (0%)	0.09	Metal casting	Not Required	Machining, grinding	0.1	Recycle	20
1	Cable sheath, 1 meter	PP (random copolym...)	Virgin (0%)	0.06	Polymer molding (injection, blow)	Not Required		0	Combust	20
1	Cable core, 1 meter	Copper, C10100, soft...	Typical %			0			Recycle	20
1	Plug body	Epoxy (mineral filler)	Virgin (0%)			Not Required			Combust	20
1	Plug pins	Brass, CuZn36, C2...	Typical %			0			Recycle	20
1	Packaging, padding	PVC cross-linked foa...	Virgin (0%)			Not Required			Combust	20
1	Packaging, box	Paper (cellulose based)	Virgin (0%)			Not Required	Cutting and trimming		Recycle	20

Joining and Finishing

Secondary Processes

"Restricted" risk flags

May.....Will damage

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Summary

The Ansys Granta EduPack software has **two resources** to help explore the materials dimension of environmental design

- 1. Selection strategies** allows selection to re-design products using eco-properties and employ systematic methods.
- 2. The Eco Audit tool** allows students to implement quick, approximate “portraits” of energy / CO₂ Eq. character of products.

Eco Audits reveal the eco-fingerprint of products and suggest approaches to making them less environmentally damaging. The Enhanced Eco Audit gives Cost information and flags restricted or critical materials risk

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Document Information

This lecture unit is part of a set of teaching resources to help introduce students to materials, processes and rational selections.

Ansys Education Resources

To access more undergraduate education resources, including lecture presentations with notes, exercises with worked solutions, microprojects, real life examples and more, visit www.ansys.com/education-resources.