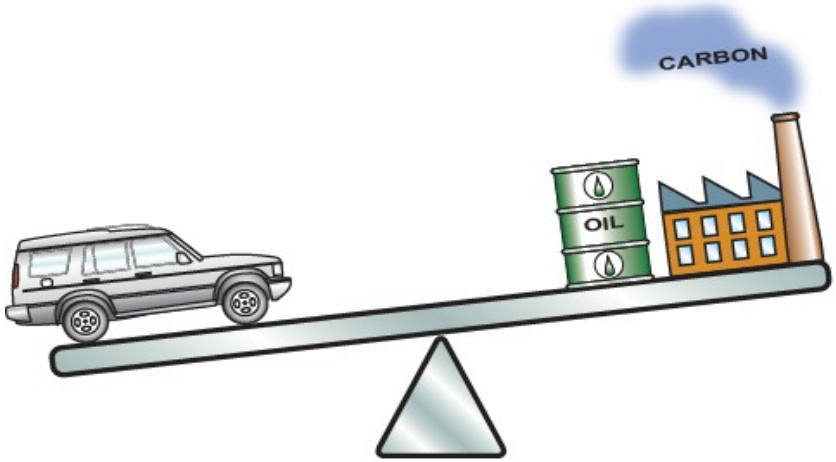


Eco-selection and the Eco-audit tool

Introducing students to life-cycle thinking

Mike Ashby

Department of Engineering
University of Cambridge

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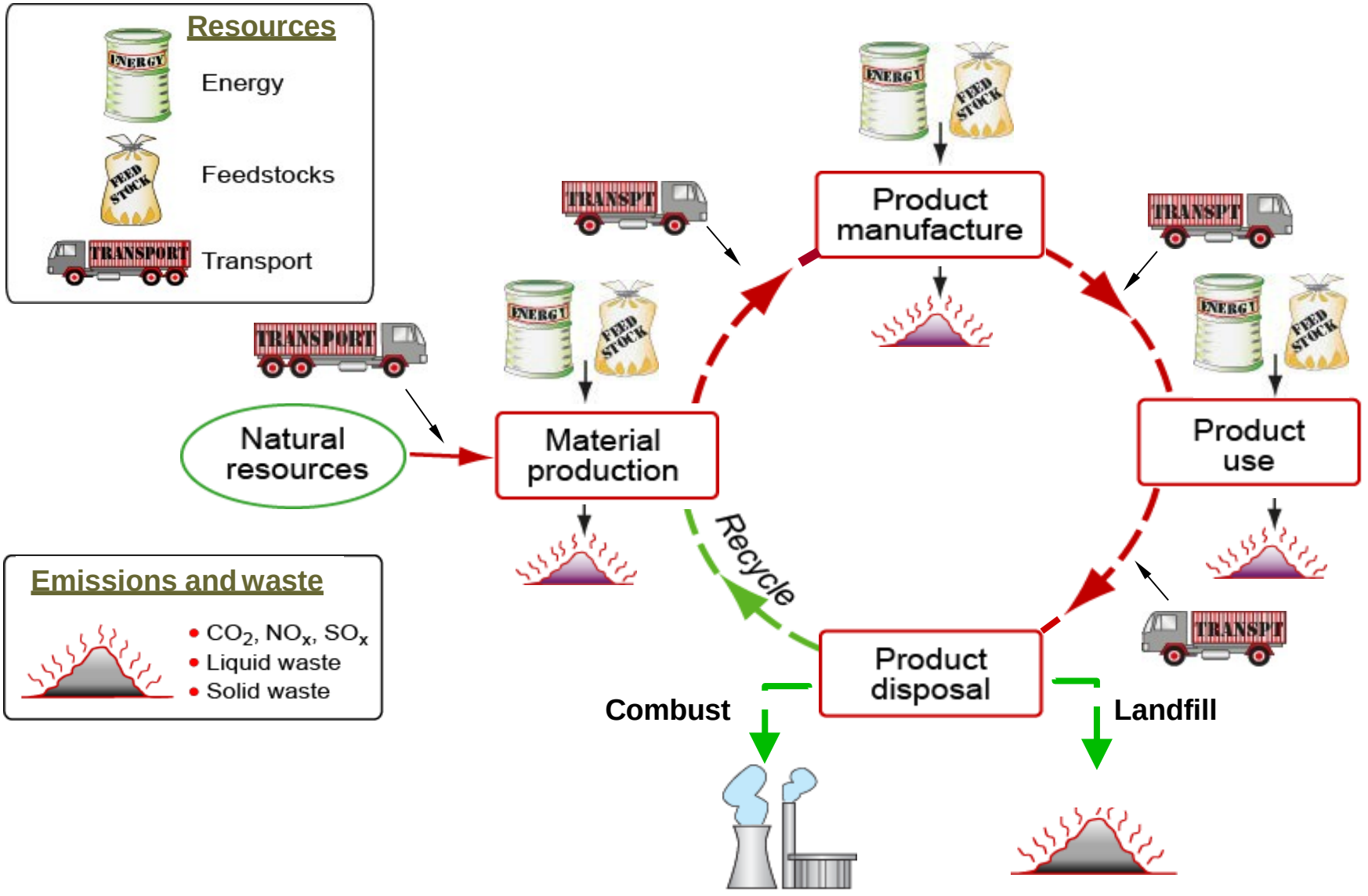
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This lecture unit is part of a set created by Mike Ashby to help introduce students to materials, processes and rational selection.

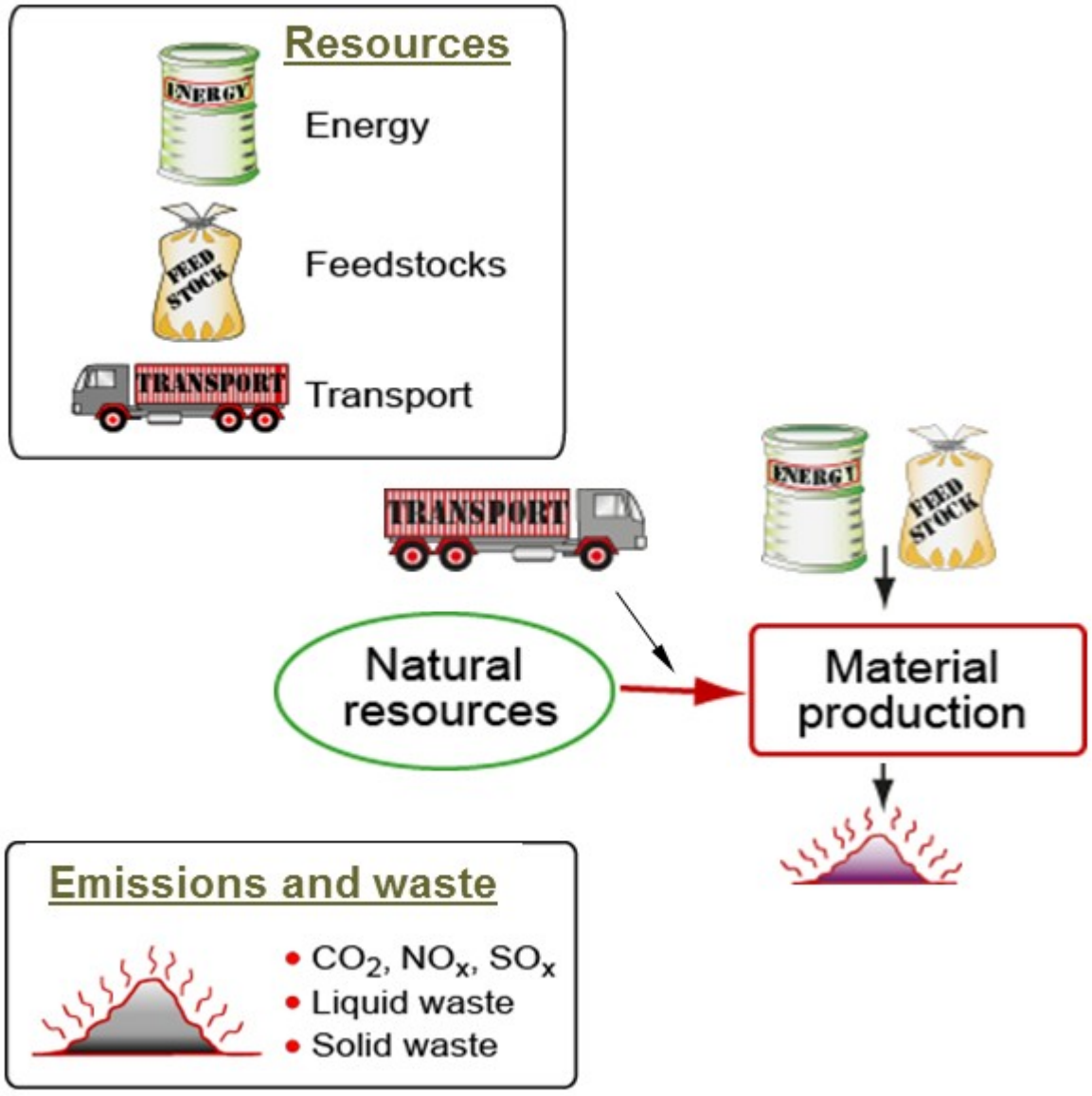
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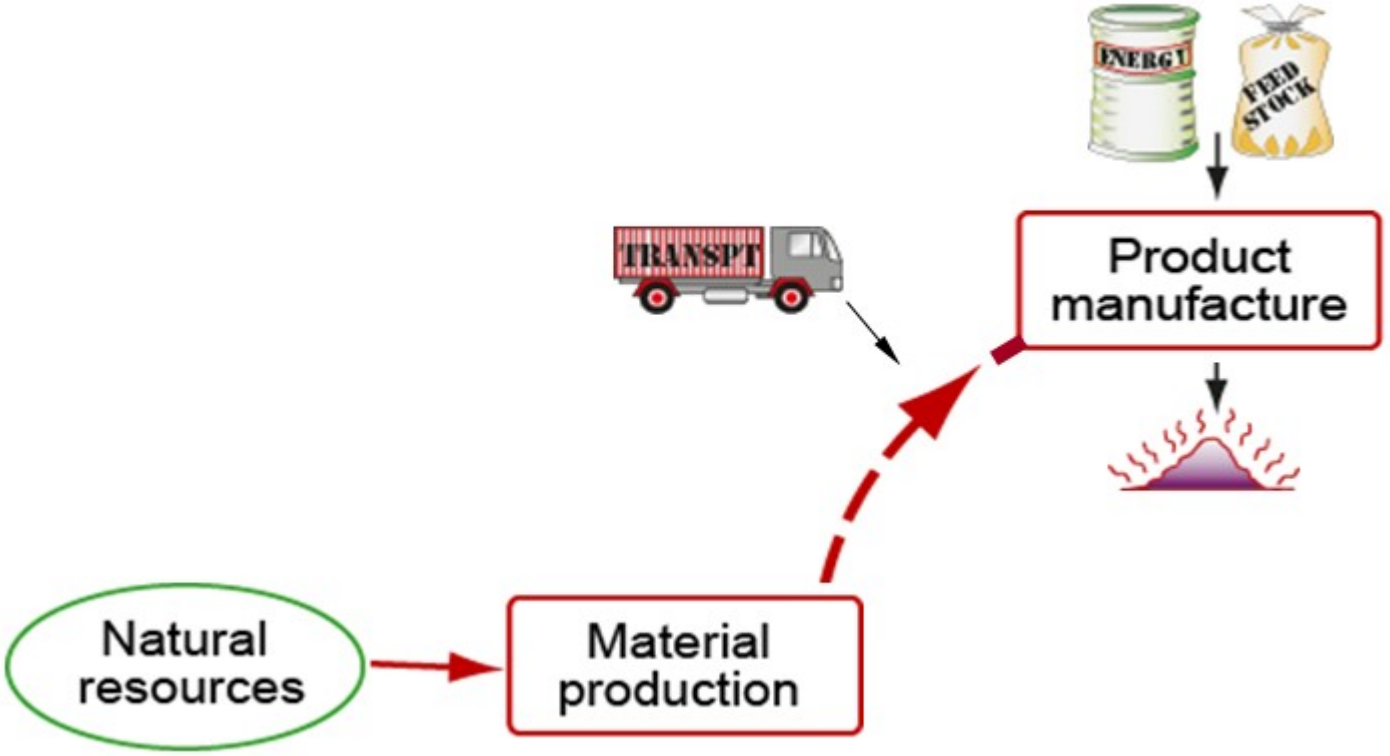
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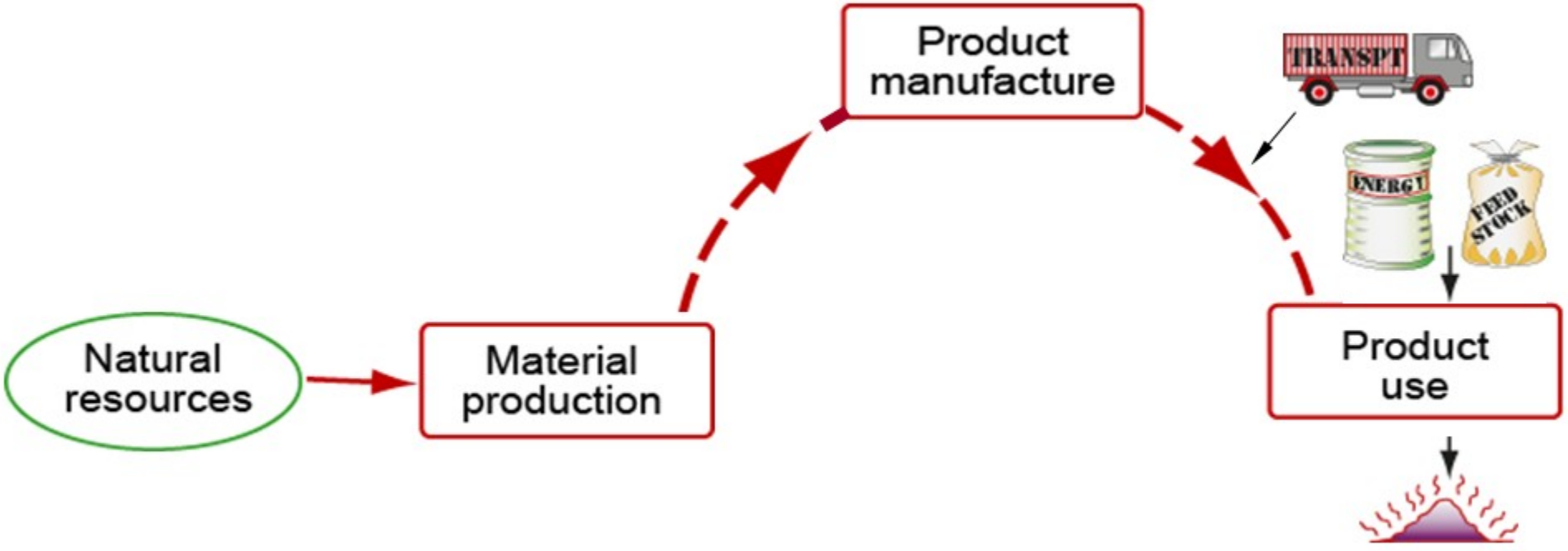
The product life-cycle

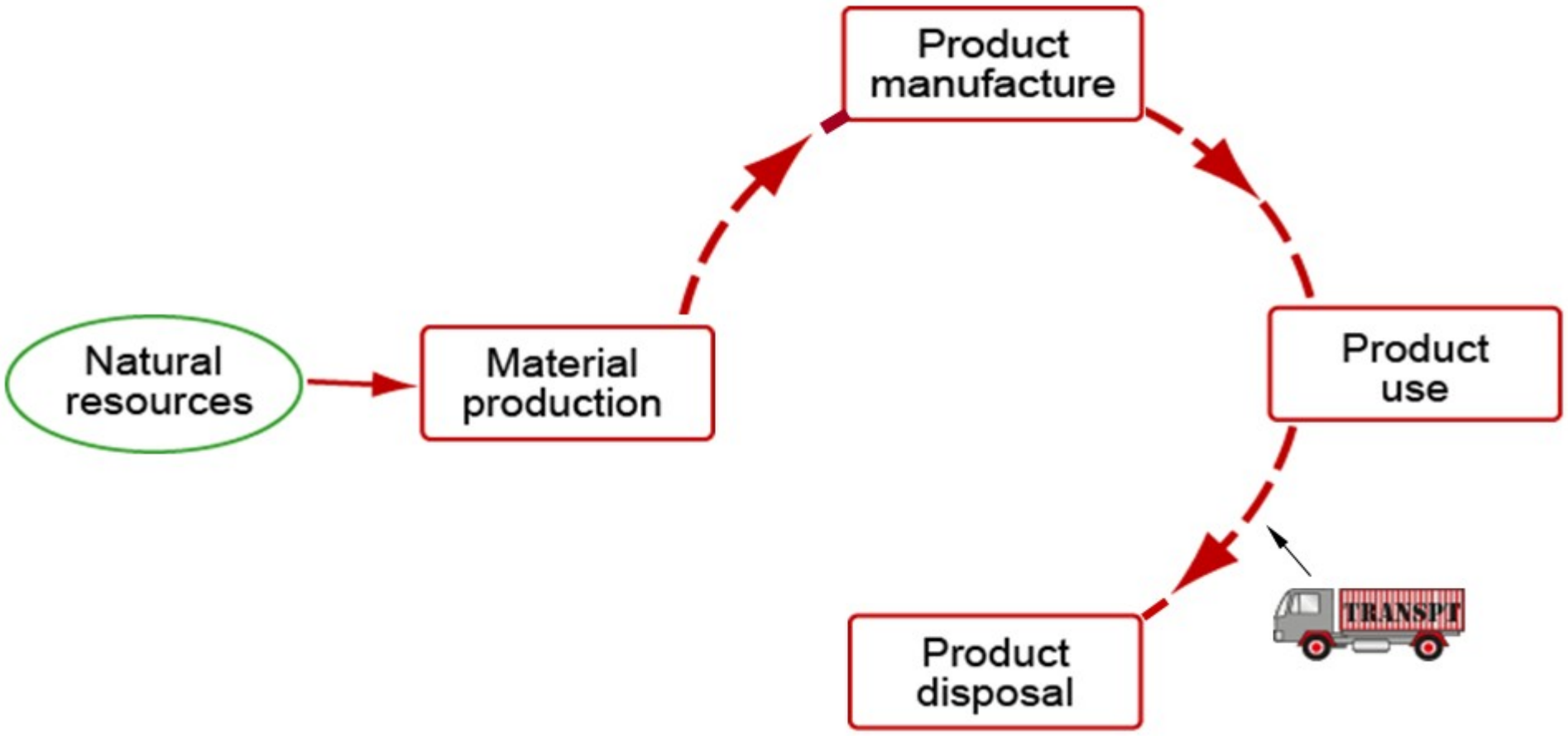


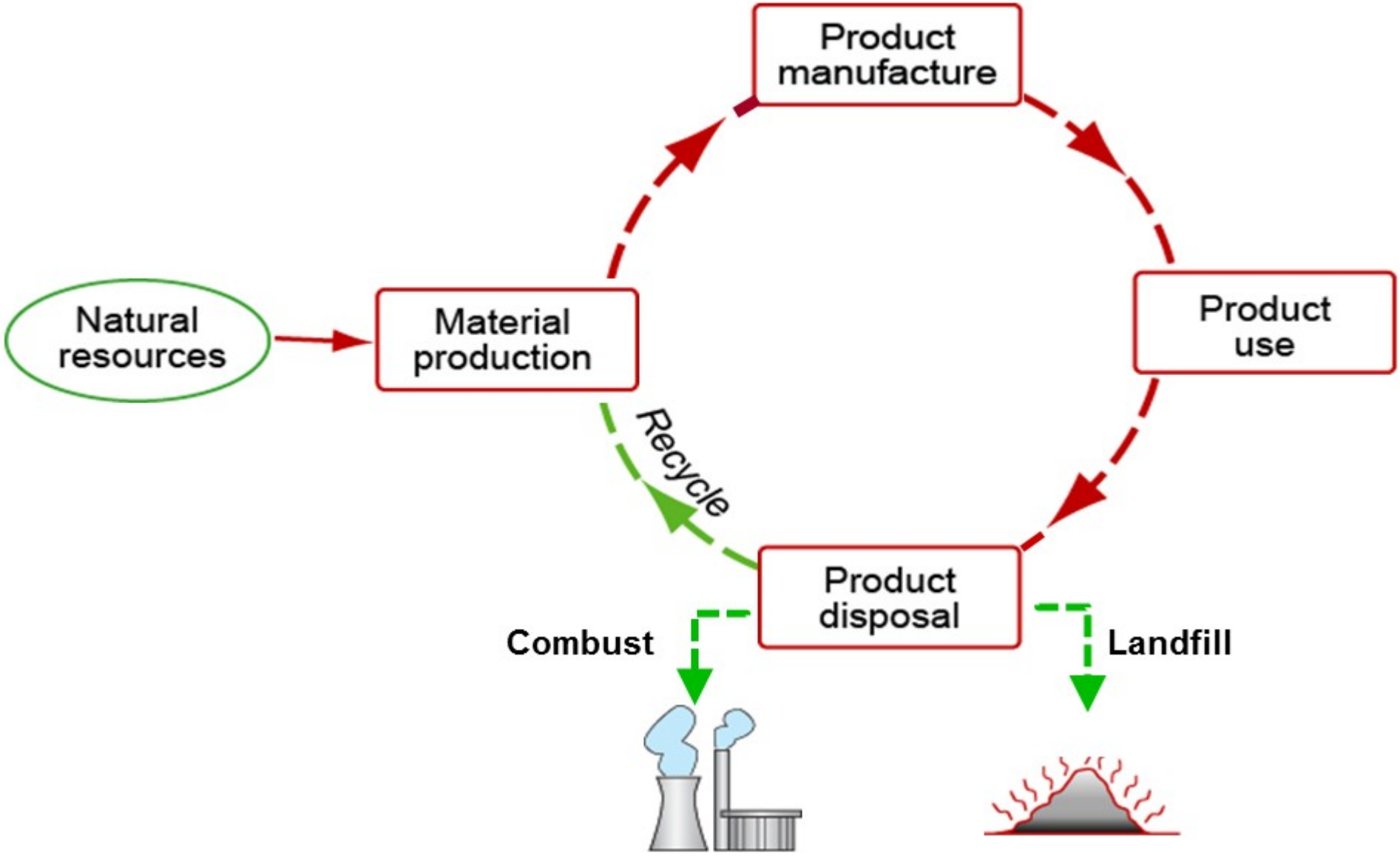
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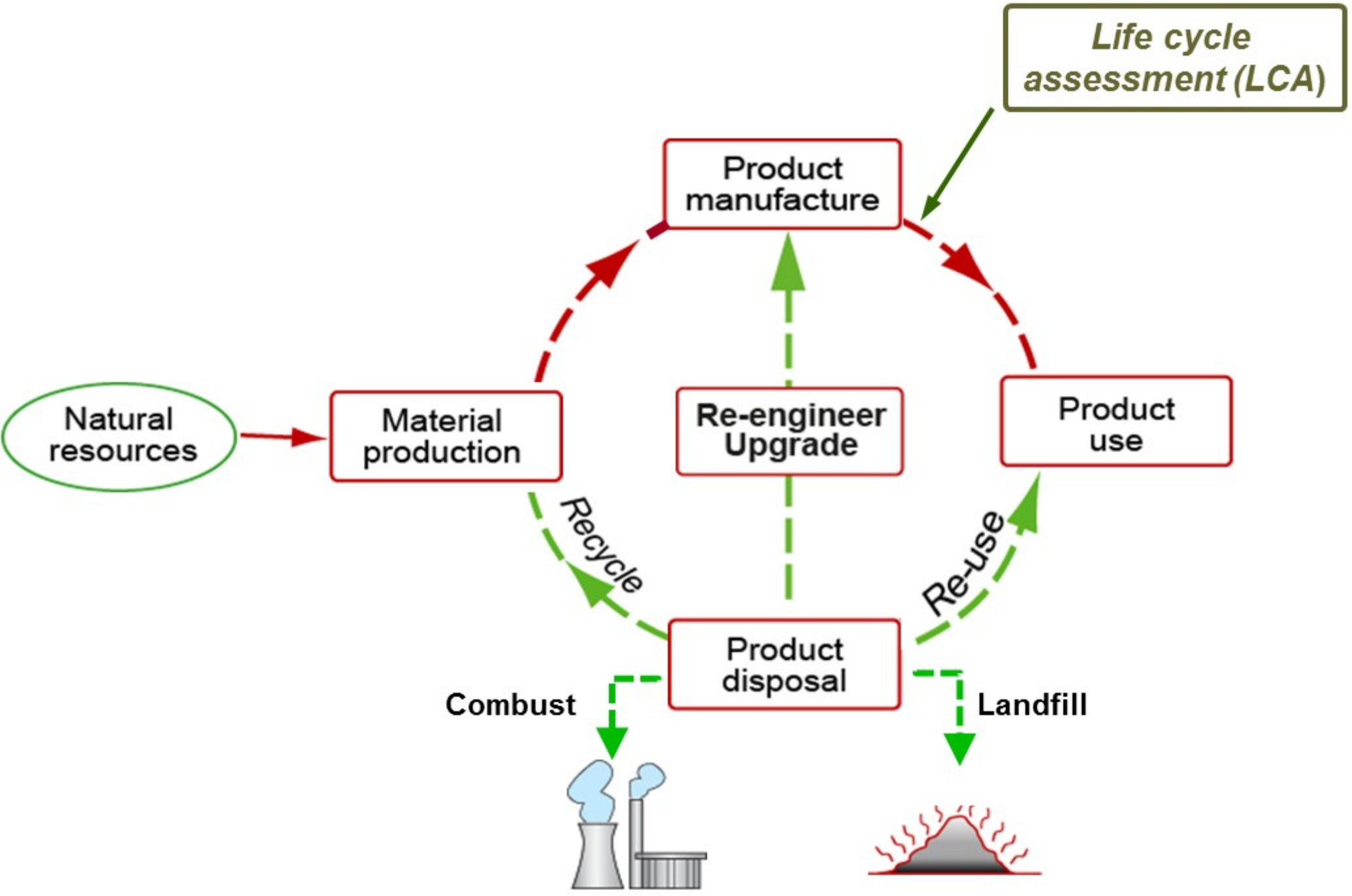

Resources
Energy
Feedstocks
Transport
TRANSPORT
ENERGY
FEED STOCK
Natural resources
Material production
Emissions and waste
• CO_2, NO_x, SO_x
• Liquid waste
• Solid waste

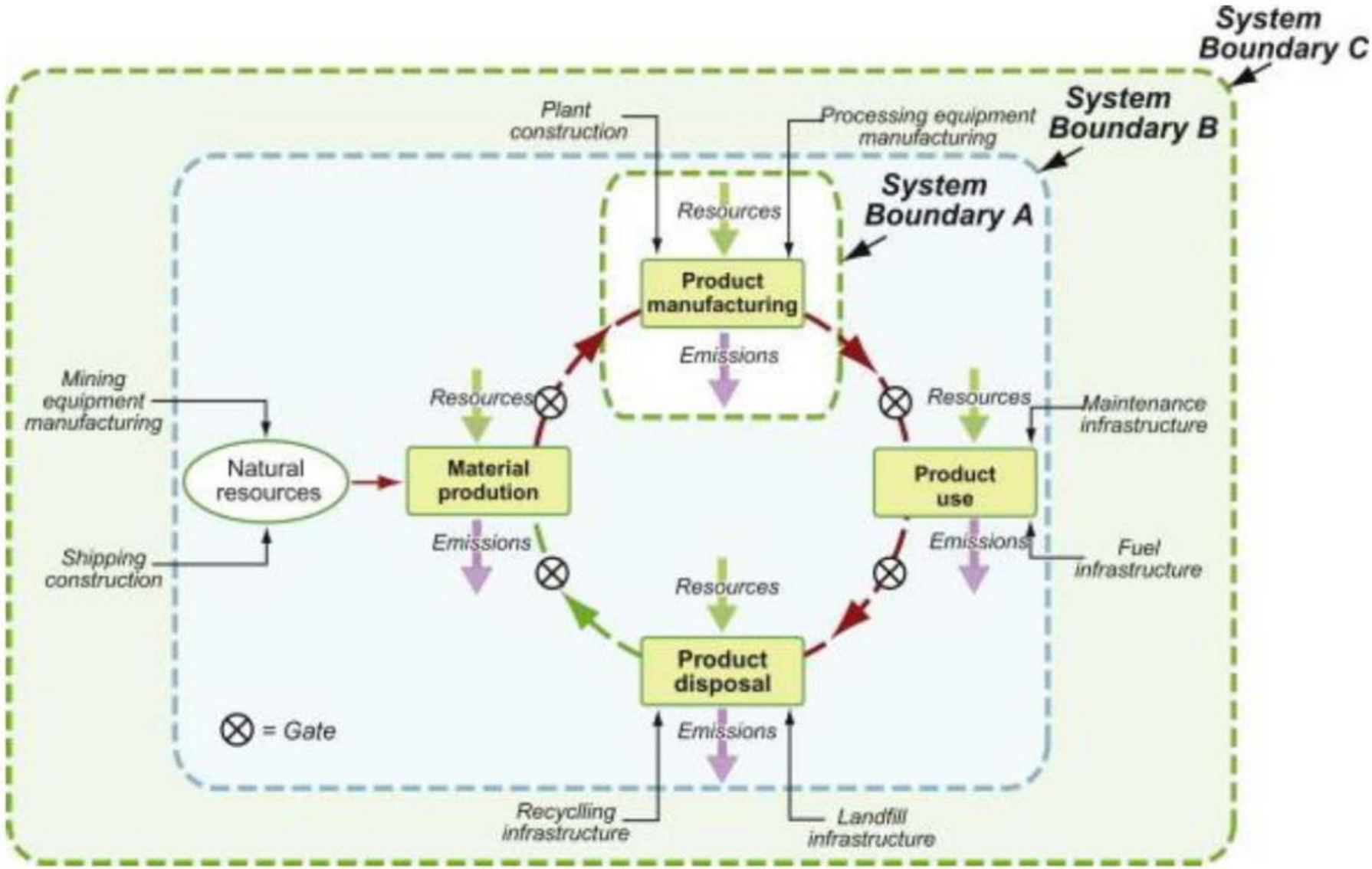

ENERGY
FEED STOCK
TRANSPT
Product manufacture
Natural resources
Material production


Product manufacture
TRANSPT
ENERGY
FEED STOCK
Natural resources
Material production
Product use


Product manufacture
Natural resources
Material production
Product use
TRANSPT
Product disposal


Product manufacture
Product use
Product disposal
Material production
Natural resources
Recycle
Combust
Landfill


Life cycle assessment (LCA)
Product manufacture
Natural resources
Material production
Re-engineer Upgrade
Product use
Recycle
Re-use
Product disposal
Combust
Landfill


System Boundary C
System Boundary B
System Boundary A
Plant construction
Processing equipment manufacturing
Resources
Product manufacturing
Emissions
Mining equipment manufacturing
Resources
Resources
Maintenance infrastructure
Natural resources
Material prodution
Product use
Shipping construction
Emissions
Emissions
Fuel infrastructure
Resources
Product disposal
= Gate
Emissions
Recyclling infrastructure
Landfill infrastructure

Life cycle assessment (LCA)

ISO 14040 series
PAS 2050

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: 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 an *"eco-indicator"* ?

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

Many LCA parameters available

Why don't we apply the concept of penalty function?

Weight factors still to be interpreted

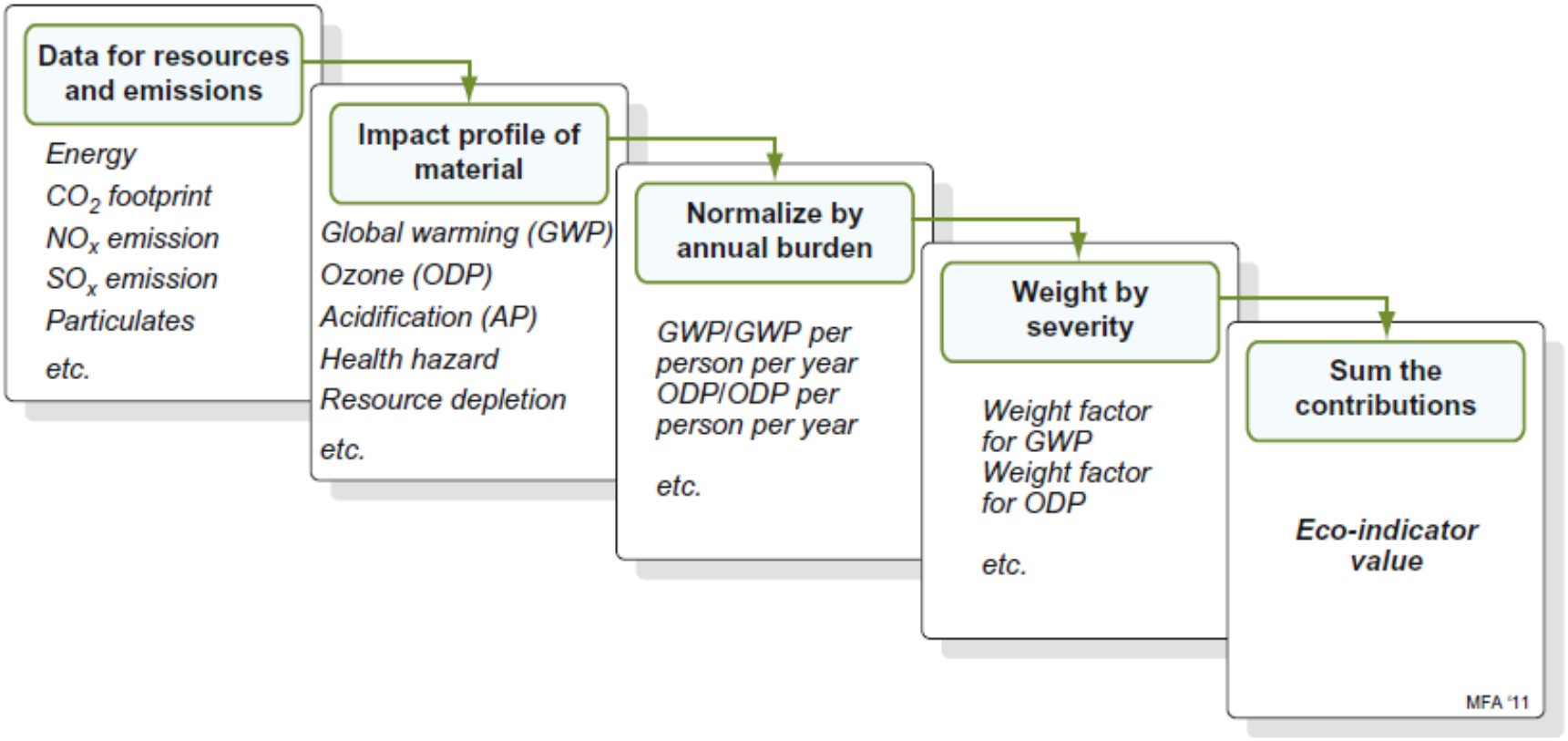


FIGURE 3.6 *The steps in calculating an eco-indicator. Difficulties arise in steps 3 and 4: there is no agreement on how to choose the weight factors.*

Differences between LCA and Eco-audit

Eco-audit=applied at the design stage

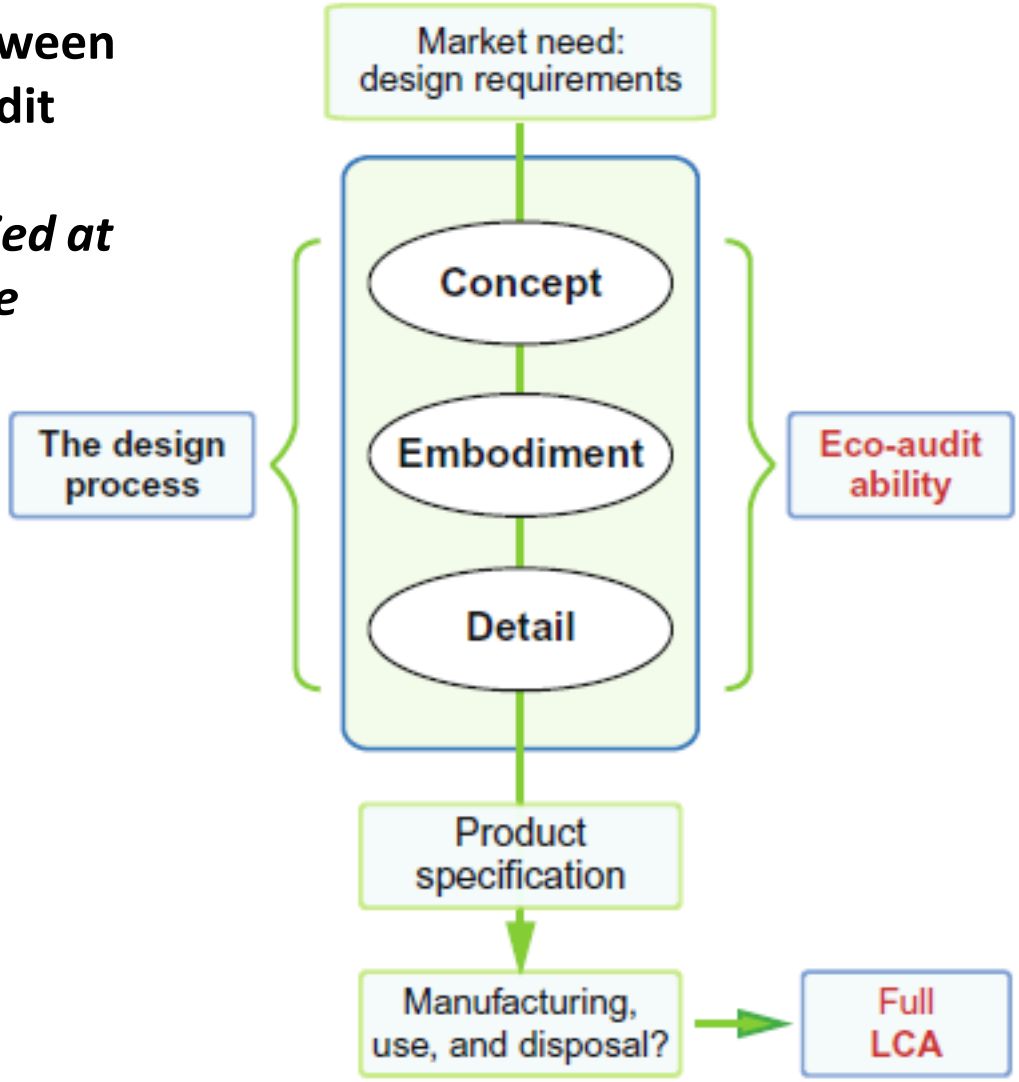
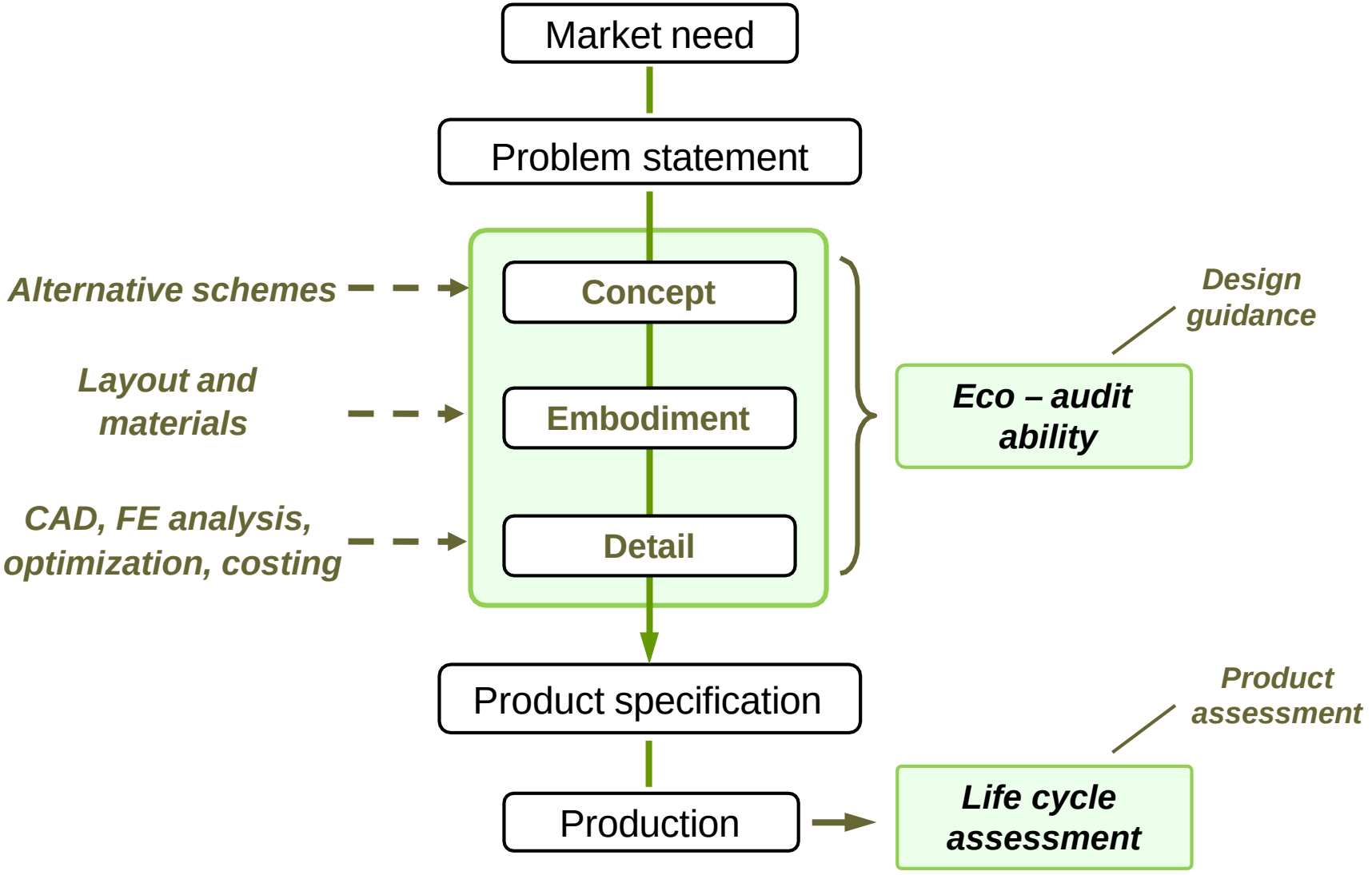


FIGURE 3.7 *An LCA is an end-of-life assessment tool. A streamlined LCA and an eco-audit are design tools.*

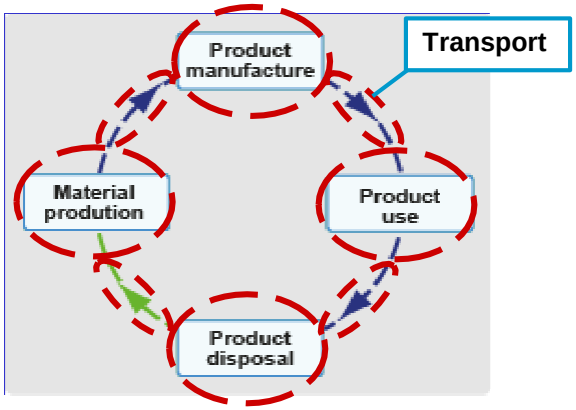
Design guidance vs. product assessment

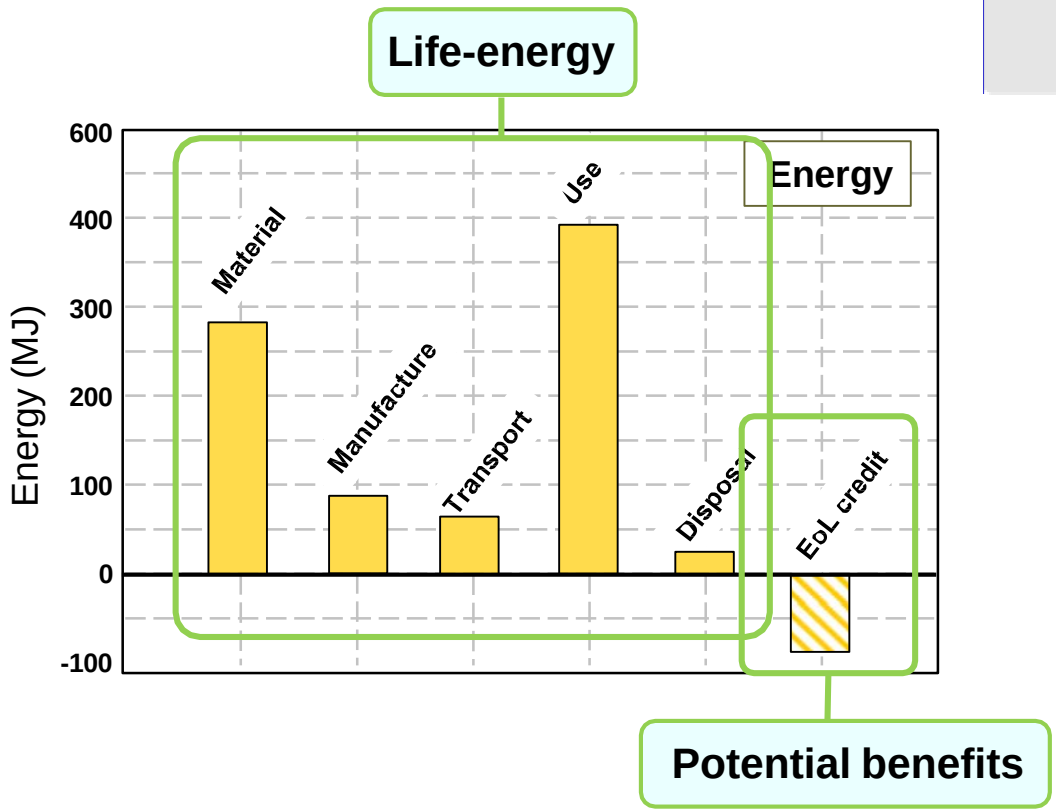


Eco-audit for design

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

- **1 resource** – ***energy*** ***(oil equivalent)***
- **1 emission** – ***CO_2 equivalent***
- **Distinguish life-phases**

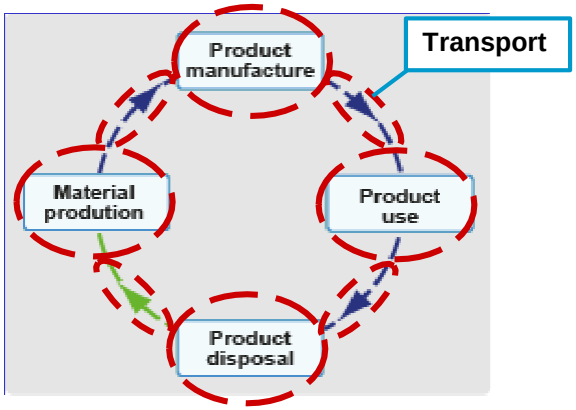


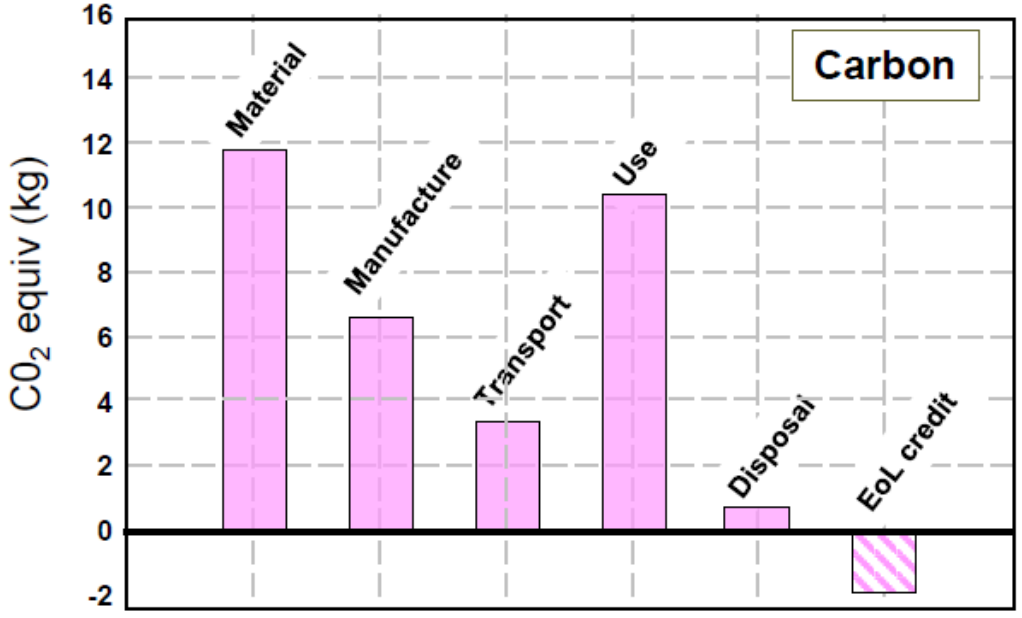


Eco-audit for design

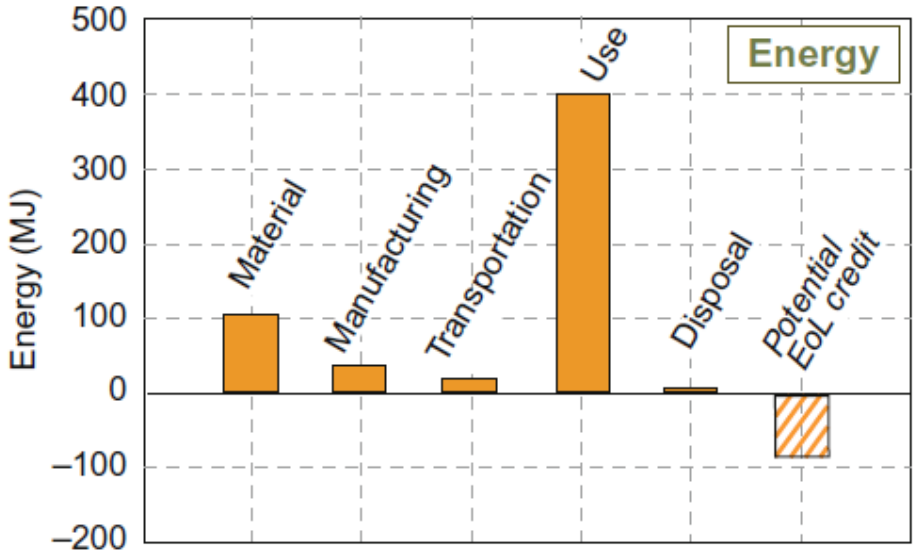
Need: Fast **Eco-audit** with sufficient precision to guide decision-making

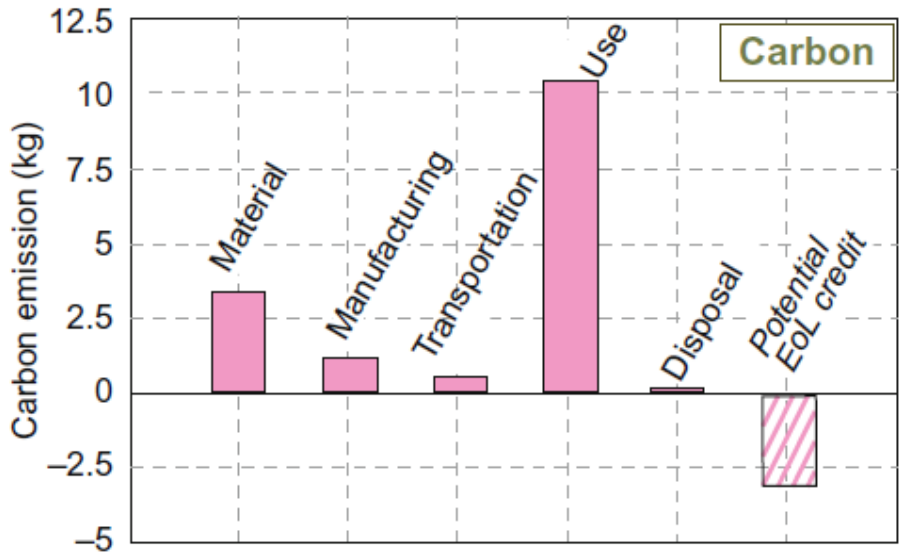
- **1 resource** – ***energy*** ***(oil equivalent)***
- **1 emission** – ***CO_2 equivalent***
- **Distinguish life-phases**





In summary, a full LCA offers the most complete and exhaustive analysis of the environmental impact of products, but it is an expensive, time-consuming tool that requires great detail, much of it unavailable until the product has been manufactured and used. To guide design decisions, particularly the choice of materials, we need tools of a different sort, ideally with the ability to carry out rapid "what if?" audits that allow the designer to explore alternative options (Figure 3.7).

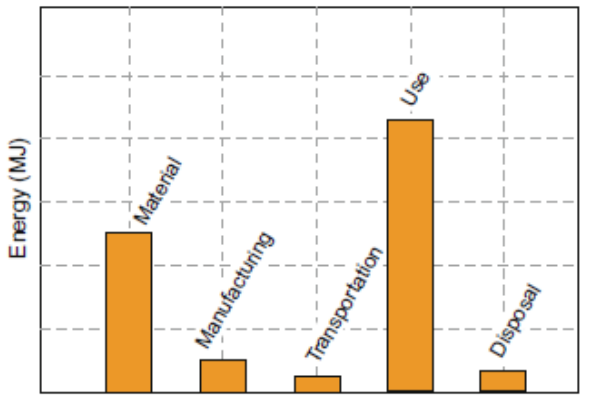




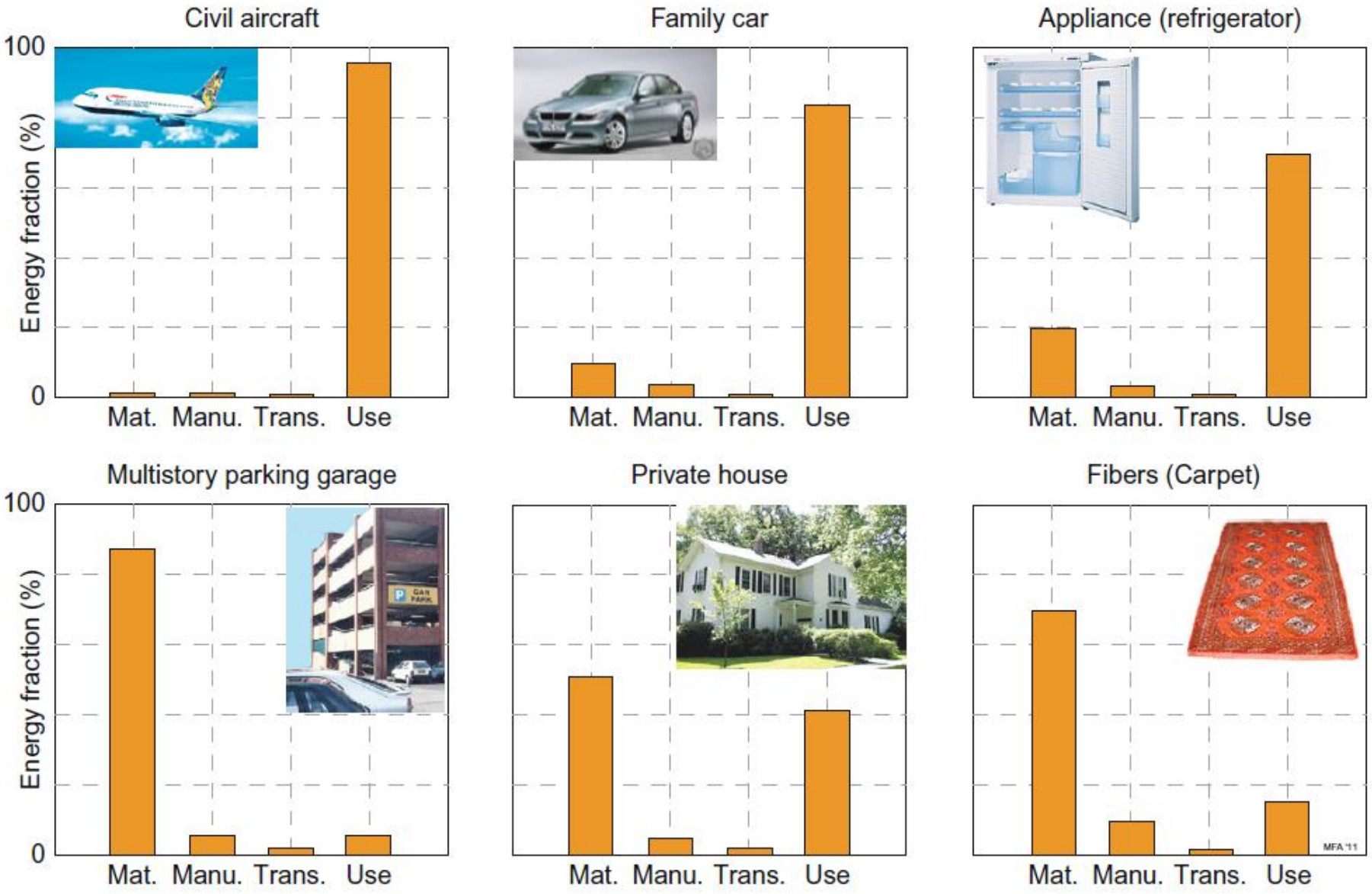
Eco-audit charts

Principles of Eco-auditing

1. ***Adopt simple metrics of environmental stress.*** As already discussed, energy consumption and CO_2 emissions are logical choices as simple metrics for environmental stress. The two are related and are understood by the public at large. Energy has the merit that it is the easiest to monitor, can be measured with relative precision, and, with appropriate precautions, can if necessary be used as a proxy for CO_2.
2. ***Distinguish the phases of life.*** Figure 3.12 suggests the breakdown—assigning a fraction of the total life-energy demands of a product to material creation, product manufacturing, transport, product use, and disposal. Product disposal can take many forms, some carrying an energy penalty, some allowing energy recycling or recovery. Because of this ambiguity, disposal has a chapter (Chapter 4) to itself.



Breakdown of energy into that associated with each life phase


Civil aircraft
Family car
Appliance (refrigerator)
Multistory parking garage
Private house
Fibers (Carpet)
Energy fraction (%)
100
0
Mat.
Manu.
Trans.
Use
MFA '11

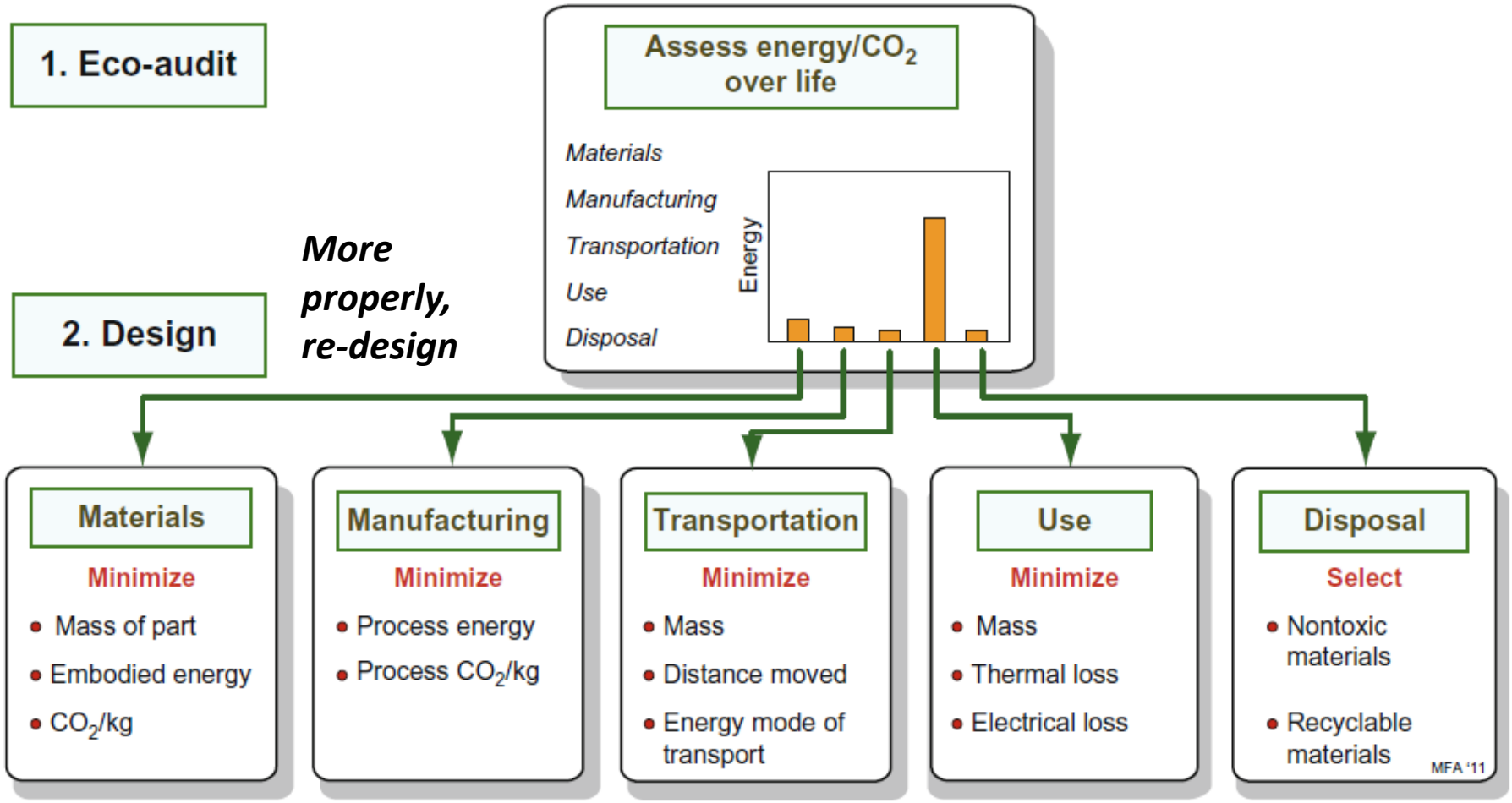

1. Eco-audit
Assess energy/CO_2 over life
Materials
Manufacturing
Transportation
Use
Disposal
Energy
2. Design
More properly, re-design
Materials
Minimize
Mass of part
Embodied energy
CO_2/kg
Manufacturing
Minimize
Process energy
Process CO_2/kg
Transportation
Minimize
Mass
Distance moved
Energy mode of transport
Use
Minimize
Mass
Thermal loss
Electrical loss
Disposal
Select
Nontoxic materials
Recyclable materials
MFA '11

Table 6.1 Eco-attributes of a material

Aluminum alloys		
Eco properties: material		
Global production, main component		37×10^6 metric ton/yr
Reserves		2.0×10^9 metric ton
Embodied energy, primary production		200–220 MJ/kg
CO_2 footprint, primary production		11–13 kg/kg
Water usage		495–1490 l/kg
Eco-indicator		710 millipoints/kg
Eco properties: processing		
Casting energy	***Observe variations: Route to different scenarios E.g. best case, worst case***	11–12.2 MJ/kg
Casting CO_2 footprint		0.82–0.91 kg/kg
Deformation processing energy		3.3–6.8 MJ/kg
Deformation processing CO_2 footprint		0.19–0.23 kg/kg
End of life		
Embodied energy, recycling		22–39 MJ/kg
CO_2 footprint, recycling		1.9–2.3 kg/kg
Recycle fraction in current supply		41–45%

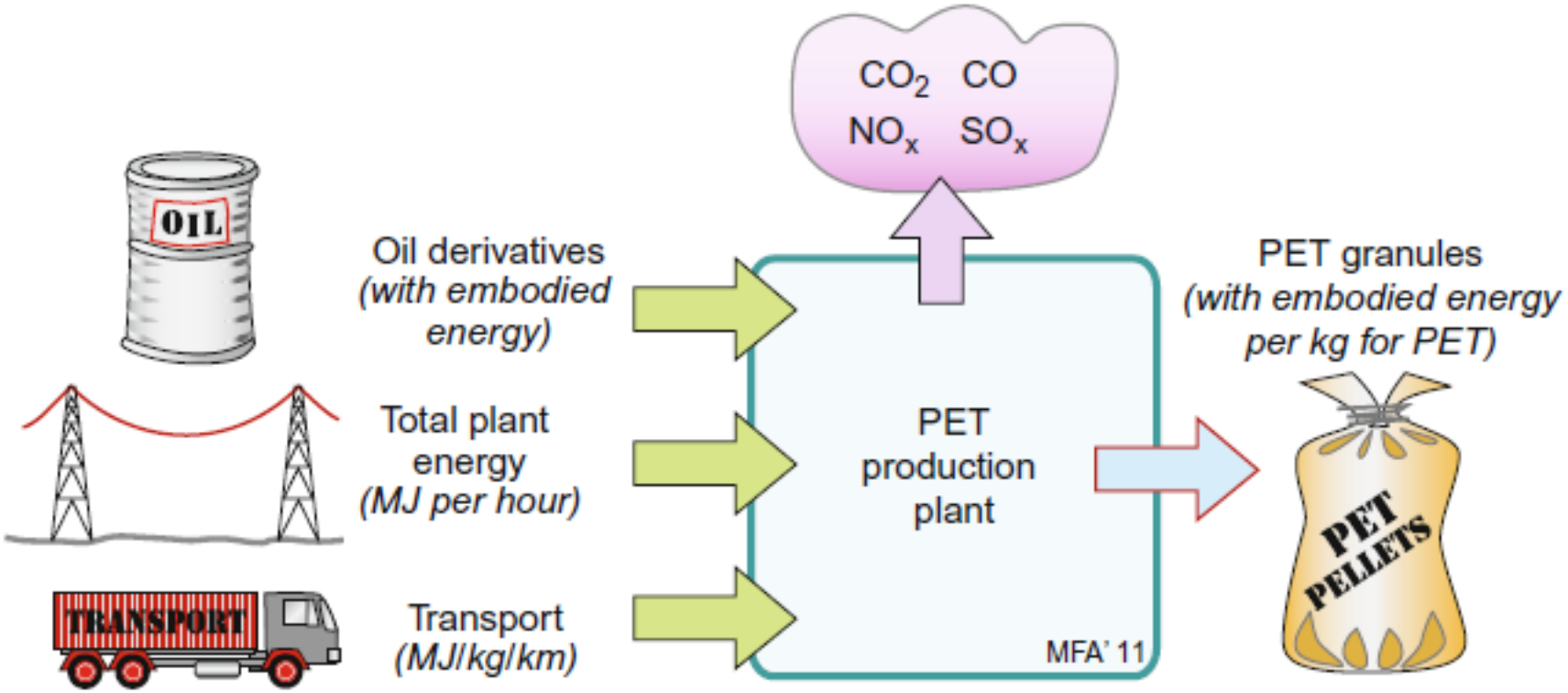
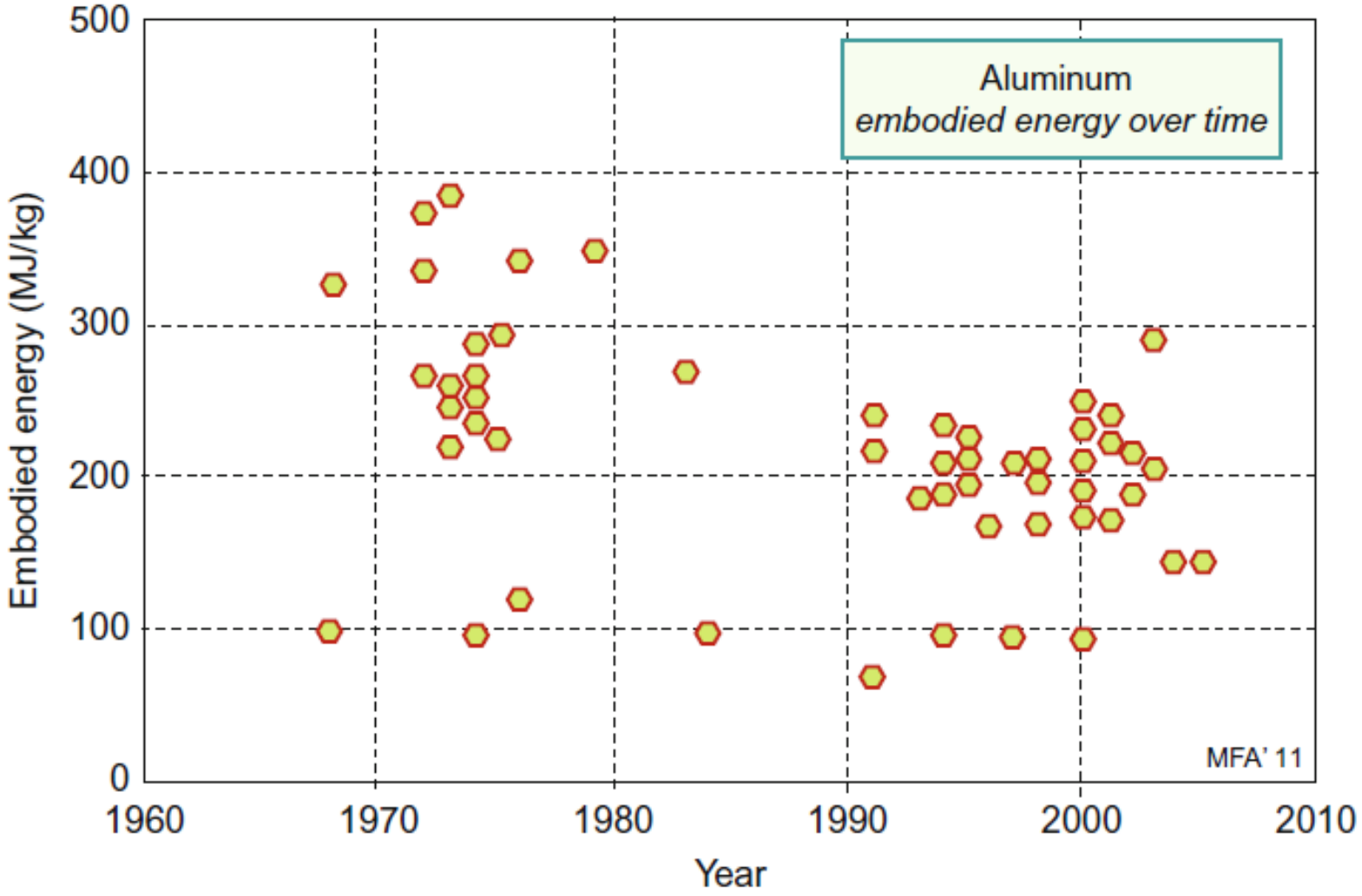


FIGURE 6.1 *The idea of embodied energy. Energy, in various forms, enters or is required by the plant. Its output is a material. The energy per kg of usable material is the embodied energy of the material.*

Normalization: energy consumption referred to oil

[1] 1 kWh = 3.6 $MJ_{electrical}$ = 3.6/η MJ_{oe} where η is the conversion efficiency of fossil fuel to electrical energy.



Data precision conditioned by history (=diffusion of best practices)

FIGURE 6.2 *Data for the embodied energy of aluminum. The mean is 204 MJ/kg, with a standard deviation of 58 MJ/kg. Using the best-characterized data only gives a mean of 210 MJ/kg with a standard deviation of 20 MJ/kg.*

Using data for embodied energy

Example: A cooking pot has a cast virgin-aluminum body and a molded phenolic handle. The body weighs 0.8 kg and the handle weighs 0.1 kg. What is the total embodied energy of the materials of the pot? If the aluminum body were replaced by one made of virgin cast iron weighing three times more, would the total embodied energy of the pot be less?

Answer: The data sheets of Chapter 15 have data for embodied energy:

Material	Embodied energy, virgin material (MJ/kg)
Aluminum alloys	210
Cast iron	29
Phenolic	79

The total embodied energy of the aluminum pot is

$$0.8 \times 210 + 0.1 \times 79 = 176 \text{ MJ}$$

The total embodied energy of the cast iron pot is

$$2.4 \times 29 + 0.1 \times 79 = 78 \text{ MJ}$$

The cast iron pot has an embodied energy that is less by 98 MJ than that of the aluminum one, despite its greater mass. In reality, the aluminum and the cast iron used in an application like this would contain considerable recycled content. This is illustrated in the next example.

Using materials with recycled content

Example: The cooking pot of the last example is, in fact, made from aluminum with a typical (43%) recycled content. The cast iron pot, too, contains the typical (67%) recycled content. How much difference does this make to the embodied energies of the pots?

Answer: The data sheet for aluminum alloys of Chapter 15 has data for typical recycled content in current supply and the embodied energy of recycled aluminum and cast iron:

Material	Embodied energy, virgin material (MJ/kg)	Typical recycle content (%)	Embodied energy, recycling (MJ/kg)
Aluminum alloys	210	43	25
Cast iron	29	67	8
Phenolic	79	0	—

The embodied energy of the materials of the aluminum pot now total

$$0.8 \times (0.57 \times 210 + 0.43 \times 25) + 0.1 \times 79 = 112 \text{ MJ}$$

Using aluminum with recycled content reduces the energy by 36%. The embodied energy of the materials of the cast iron pot now total

$$2.4 \times (0.33 \times 29 + 0.67 \times 8) + 0.1 \times 79 = 44 \text{ MJ}$$

a reduction of 44%.

Precious metals in engineering structures

Example: A catalytic converter has a steel container weighing 1 kg and an extruded alumina honeycomb core weighing 0.5 kg, which is coated with 1 gram of a platinum catalyst. Which of the three components contributes most to the embodied energy of the materials of the converter?

Answer: From Table 6.2 and the data sheets of Chapter 15.

Material	Embodied energy (MJ/kg)
Low-carbon steel (Ch.15)	26.5
Alumina (Ch. 15)	52.5
Platinum (Table 6.5)	270,000

Metal	Embodied energy (MJ/kg)	Carbon footprint (kg/kg)	Unique applications
Silver	1.4×10^3–1.55×10^3	95–105	Photosensitive compounds, dentistry
Gold	240×10^3–265×10^3	14,000–15,900	Corrosion-free contacts, dentistry
Palladium	5.1×10^3–5.9×10^3	404–447	Catalysis, hydrogen purification
Rhodium	13.5×10^3–14.9×10^3	1,000–1,200	Catalysis
Platinum	257×10^3–284×10^3	14,000–15,500	Catalysis, electrodes, contacts
Iridium	2×10^3–2.2×10^3	157–173	Catalysis, electrodes, high-temperature igniters

Precious metals in engineering structures

Example: A catalytic converter has a steel container weighing 1 kg and an extruded alumina honeycomb core weighing 0.5 kg, which is coated with 1 gram of a platinum catalyst. Which of the three components contributes most to the embodied energy of the materials of the converter?

Answer: From Table 6.2 and the data sheets of Chapter 15.

Material	Embodied energy (MJ/kg)
Low-carbon steel (Ch.15)	26.5
Alumina (Ch. 15)	52.5
Platinum (Table 6.5)	270,000

The contribution of 1 kg of steel to the embodied energy of the converter is 26.5 MJ, that of 0.5 kg of alumina ceramic is 26 MJ, and that of 1 gram of platinum is 270 MJ. The platinum contributes much more than the sum of the others, despite the tiny quantity.

Improving container or core will have no impact!
Improvements must pass by change of catalyst/change of reaction

Energy and carbon footprint of electronics

Example: A fire alarm has two AA Ni-Cd batteries, small-device electronics weighing 30 grams, and a phenolic casing weighing 400 grams. Which of these makes the largest contribution to the embodied energy and carbon footprint?

Answer: From Table 6.3 and the data sheet for phenolic in Chapter 15 we have

Component and material	Embodied energy	Carbon footprint
Ni-Cd AA battery	3 MJ/unit	0.2 kg/unit
System, small electronic device	3,000 MJ/kg	300 kg/kg
Phenolic	79 MJ/kg	2.65 kg/kg

Thus the embodied energy of the batteries is $2 \times 3 = 6$ MJ, that of the electronics is $0.03 \times 3{,}000 = 90$ MJ, and that of the casing is $0.4 \times 79 = 32$ MJ. The electronics accounts for more energy than the other components combined. The same is true for the carbon footprint.

Materials selection for the case is practically useless for eco optimization
…but still works for other requirements (e.g. reduced overall thickness, stiffness, etc.)

Embodied energies of structure and enclosure

Example: The structure of a steel-framed building requires, per square meter of floor area, 625 kg of standard concrete (foundation) and 86 kg of steel (100% recycled). The enclosure, per m^2 of floor, requires 0.2 m^3 of fiberglass insulation and 6.6 m^2 of ¾-inch (19 mm) plywood. What, approximately, is the embodied energy of structure plus enclosure?

Answer: Drawing data from Table 6.4, we find the embodied energy of the structure is

$$625 \times 1.14 + 86 \times 7.3 = 1{,}340 \text{ MJ} = 1.34 \text{ GJ}$$

That for ¾-inch plywood is

$$0.019 \times 5{,}720 = 109 \text{ MJ}/m^2$$

So the embodied energy of the enclosure is

$$0.2 \times 970 + 6.6 \times 109 = 913 \text{ MJ} = 0.91 \text{ GJ}$$

The total embodied energy is thus 3.02 GJ, of which the structure forms 60% and the enclosure 40%.

Table 6.4 Approximate embodied energies and carbon footprints of building materials

	Density (kg/m^3)	Embodied energy		Carbon footprint	
		MJ/kg	MJ/m^3	kg/kg	kg/m^3
Primary structure					
Aggregate	1,500	0.10	150	0.006	9
Brick, common	2,100	2.8	5,880	0.22	462
Concrete 30 MPa	2,450	1.3	3,180	0.095	233
Concrete block	2,500	0.94	2,350	0.061	151
Concrete, high-volume fly-ash	2,010	1.14	2,290	0.068	137
Concrete, precast	1,390	2.00	2,780	0.12	167
Concrete, reinforced (8 wt% steel)	2,910	2.49	7,250	0.21	611
Concrete, standard	2,390	1.14	2,700	0.1	239
Soil cement (rammed earth)	1,950	0.42	819	0.03	55
Steel, virgin	7,850	27	212,000	1.8	14,100
Steel, 100% recycled	7,850	7.3	57,300	0.57	4,470
Steel, typical 42% recycled content	7,850	18.7	147,000	1.23	9,660
Straw bale	125	0.22	27	−099	−12
Timber, structural	550	7.3	1,380	0.42	230
Enclosure					
Aluminum, virgin	2,700	210	567,000	12	324,000
Aluminum, 43% recycled content	2,700	131	354,000	7.7	220,800
Duck (cellulose-based fabric)	980	72	7,060	4.5	4.230
GFRP (sheet molding compound)	1,900	115	220,000	8.1	1,540

Manufacturing = new eco contributions

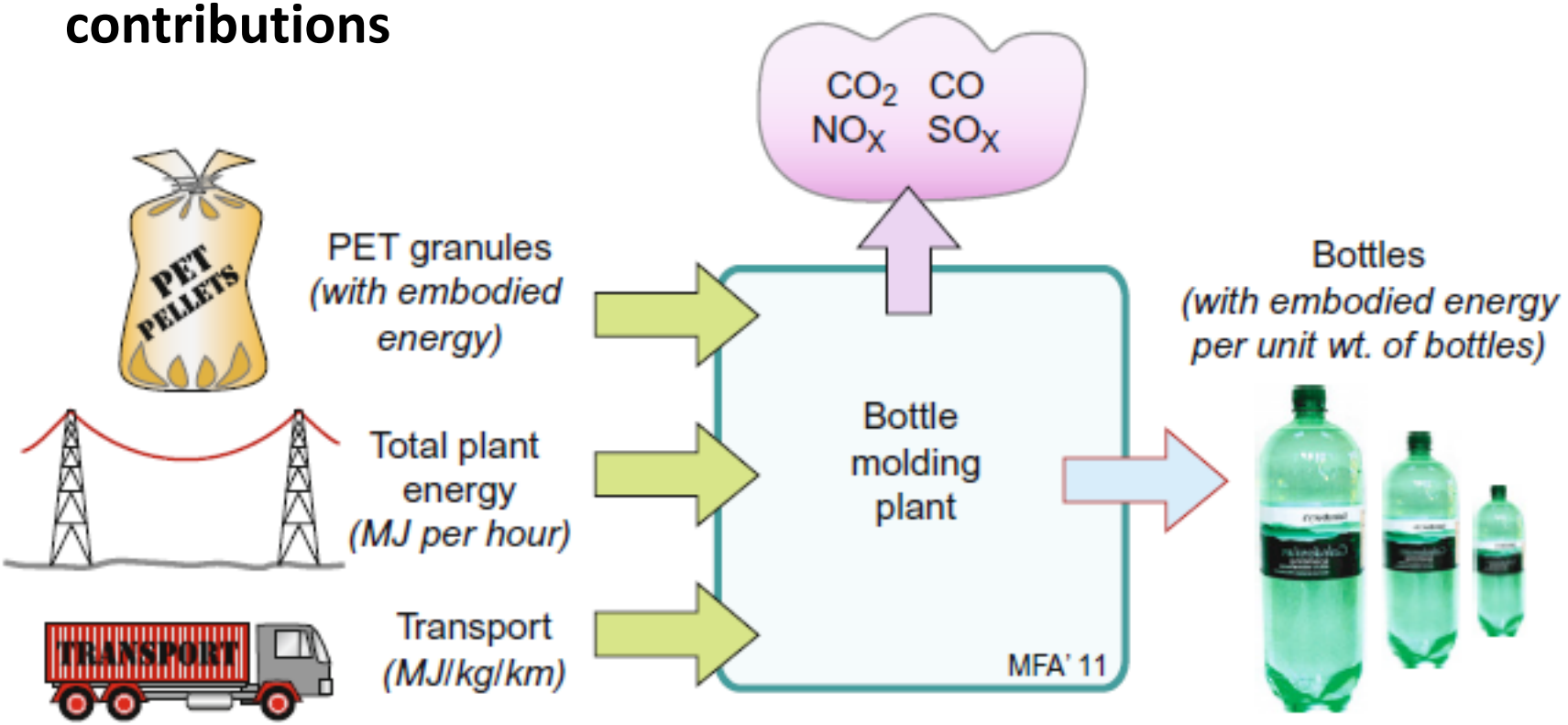


FIGURE 6.3 *Manufacturing—here, the blow-molding of PET bottles*

Table 6.5(a) Primary shaping processes

Material	Shaping process	Typical range of energies (MJ/kg)	Carbon, $CO_{2,eq}$ (kg/kg)
Metals	Casting	8–12	0.4–0.6
	Rough rolling, forging	3–5	0.15–0.25
	Extrusion, foil rolling	10–20	0.5–1.0
	Wire drawing	20–40	1.0–2.0
	Metal powder forming	20–30	1–1.5
	Vapor phase methods	40–60	2–3
Polymers	Extrusion	3.1–5.4	0.16–0.27
	Molding	11–27	0.55–1.4
Ceramics	Ceramic powder form	20–30	1–1.5
Glasses	Glass molding	2–4	0.1–0.2
Hybrids	Compression molding	11–16	1.6–0.5
	Spray-/Lay up	14–18	0.7–0.9
	Filament winding	2.7–4.0	0.14–0.2
	Autoclave molding	100–300	5–15

Table 6.5(b) Secondary processes: machining

Process type	Variants	Range of energies (MJ/kg removed)	Carbon, $CO_{2,eq}$ (kg/kg removed)
Machining	Heavy	0.8–2.5	0.06–0.17
	Finishing (light)	6–10	0.4–0.7
	Grinding	25–35	1.8–2.5
	Water jet, EDM, Laser	500–5000	35–350

Table 6.5(c) Secondary processes: joining

Process type	Variants	Typical range of energies	Typical range of carbon, $CO_{2,eq}$
Welding	Gas welding	1–2.8 MJ/m	0.055–0.15 kg/m
	Electric welding	1.7–3.5 MJ/m	0.12–0.25 kg/m
Fasteners	Fasteners, small	0.02–0.04 MJ/fastener	0.0015–0.003/fastener
	Fasteners, large	0.05–0.1 MJ/fastener	0.0037–0.0074/fastener
Adhesives	Adhesives, cold	7–14 MJ/m^2	1.3–2.8 kg/m^2
	Adhesives, heat-curing	18–40 $MJ.m^2$	3.2–7.0 kg/m^2

Table 6.5(d) Secondary processes: finishing

Process type	Variants	Typical range of energies (MJ/m^2)	Typical range of $CO_{2,eq}$ (kg/m^2)
Painting	Painting	50–60	0.63–0.095
	Baked coatings	60–70	0.9–1.3
	Powder coating	67–86	3.7–4.6
Plating	Electroplating	80–100	4.4–5.3

Using process energies

Example: A large connecting rod is cast from virgin aluminum. The bores are finished by light machining, removing 0.05 kg of metal. The finished connecting rod weighs 3.2 kg. It is suggested that machining the connecting rod from a solid, cold-rolled aluminum blank would give a higher-quality product. The starting blank weighs 5 kg.

Comparison of two processes



Heavy (coarse) machining is used for all but the finishing of the bores. Assuming virgin aluminum is used and that the machinings are not recycled, what is the energy penalty of taking the machine-from-solid option?

Answer: Drawing data from Table 6.5(b) and from the data sheets of Chapter 15 we find:

Material and process step: aluminum alloy connecting rod	**Energy**	**Units**
Embodied energy (Ch.15)	210	MJ/kg
Casting energy (Ch.15)	11.6	MJ/kg
Deformation processing energy (Ch.15)	5.1	MJ/kg
Heavy machining energy (Table 6.2)	1.7	MJ/kg removed
Light machining energy (Table 6.2)	8.0	MJ/kg removed

Summing the embodied energy of the aluminum, here are the primary process energy and the machining energies we find for the cast connecting rod

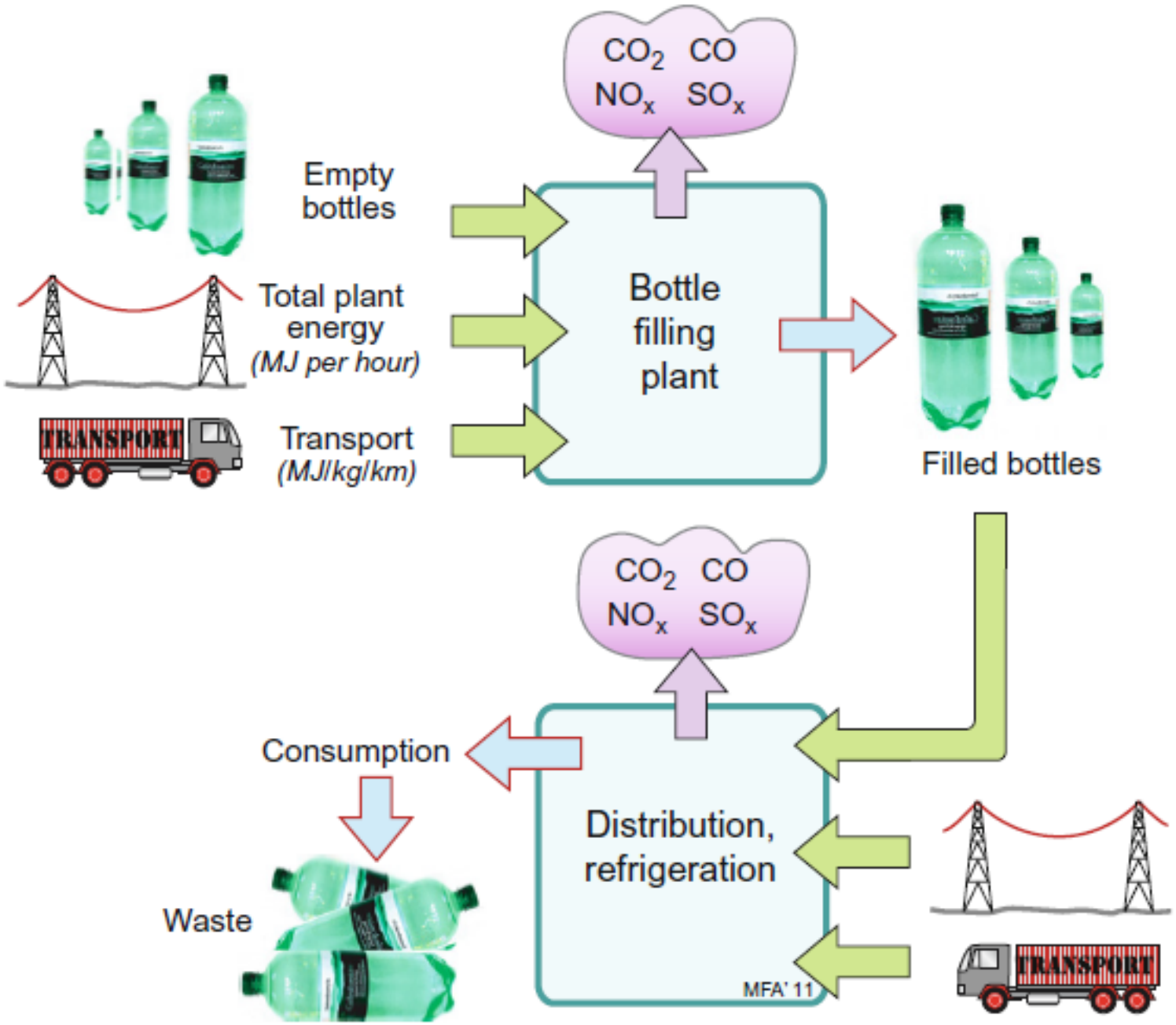
$$3.2 \times (210 + 11.6) + 0.05 \times 8.0 = 710 \text{ MJ}$$

and for the con-rod machined from solid

$$5 \times 210 + (5 - 3.2) \times 1.7 + 0.05 \times 8.0 = 1{,}053 \text{ MJ}$$

The machine-from-solid route requires 48% more energy than the casting route. But this ignores the energy recovery possible by promptly recycling the machinings. We return to this when we discuss recycling.

Comparison of two processes: can we add quality? Yes, with penalty function Z


CO_2 CO
NO_x SO_x
Empty bottles
Total plant energy
(MJ per hour)
Transport
(MJ/kg/km)
TRANSPORT
Bottle filling plant
Filled bottles
CO_2 CO
NO_x SO_x
Consumption
Waste
Distribution, refrigeration
MFA' 11
TRANSPORT

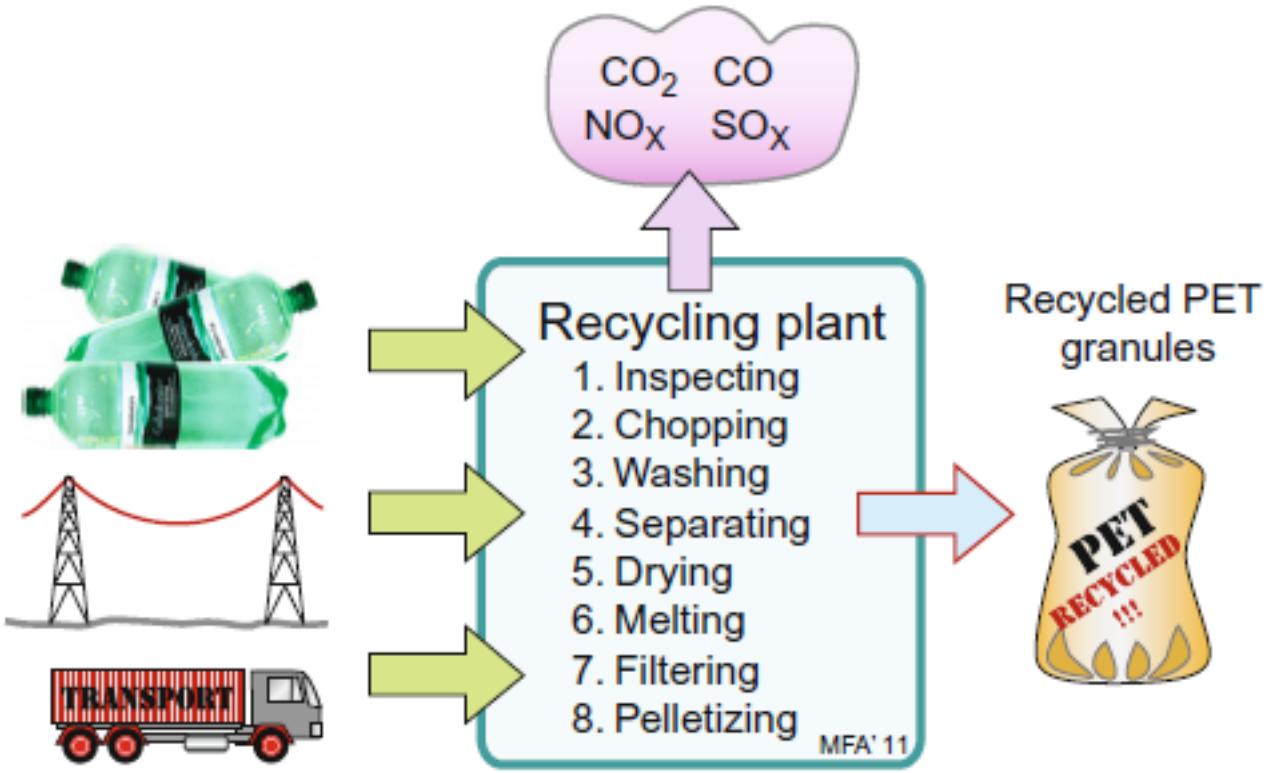


FIGURE 6.5 *Recycling. Many steps are involved, all of which consume some energy, but the embodied energy of the material is conserved.*

Table 6.6 Typical recycling data

Material	Recycled fraction in current supply[(1)] (%)	Embodied energy, virgin material (MJ/kg)	Embodied energy, recycled material (MJ/kg)	Ratio of recycled to virgin energies (%)
Aluminum	36	210	26	12
Steel	42	26.5	7.3	27
Copper	42	58	13.5	23
Lead	72	27	7.4	27
PET	21	85	39	46
PP	5	74	50	67
Glass	24	10.5	8.2	78
Paper	72	45	20	44

Recycling of prompt scrap

Example: An earlier example compared a cast aluminum connecting rod with one machined from a solid blank. The cast rod required 710 MJ for materials and manufacturing; the one machined from a solid blank took 1,053 MJ, assuming that the 1.8 kg of metal machined-off was not recycled. In practice 100% of it would be recycled. The difference between the embodied energy of virgin and recycled aluminum is a measure of the energy recovered by doing so. How much does this change the energy total for the connecting rod machined from a solid blank?

Material and process step: aluminum alloy connecting rod	**Energy**	**Units**
Embodied energy (Ch.15)	210	MJ/kg
Embodied energy, recycling (Ch. 15)	25	MJ/kg

The estimated energy recovered by recycling is

$$210 - 25 = 185 \text{ MJ/kg}$$

Thus the energy "credit" from recycling the machined metal is

$$1.8 \times 184 = 331 \text{ MJ}$$

This reduces the total energy demand of the machined-from-solid connecting rod to 722 MJ, barely more than that of the cast connecting rod.

Energy balances with recycling

Material	Recycled fraction in current supply[(1)] (%)	Embodied energy, virgin material (MJ/kg)	Embodied energy, recycled material (MJ/kg)	H_r/H_p Ratio of recycled to virgin energies (%)
Aluminum	36	210	26	12
Steel	42	26.5	7.3	27
Copper	42	58	13.5	23
Lead	72	27	7.4	27
PET	21	85	39	46
PP	5	74	50	67
Glass	24	10.5	8.2	78
Paper	72	45	20	44

H_p — Primary production energy

H_r

The recycling of Al is much easier than that of glass

Reusing glass cullet implies risks of poor quality of products (defects)

Updated manufacturing energy $H_p^* = H_p \cdot (1-r) + r \cdot H_r$

Manufacturing energy with recycled material, at **constant product quality**

Energy saving $\Delta H_p = H_p - H_p^* = H_p - H_p \cdot (1-r) - r \cdot H_r = r \cdot (H_p - H_r)$

Previous lesson

User inputs, 100 bottles

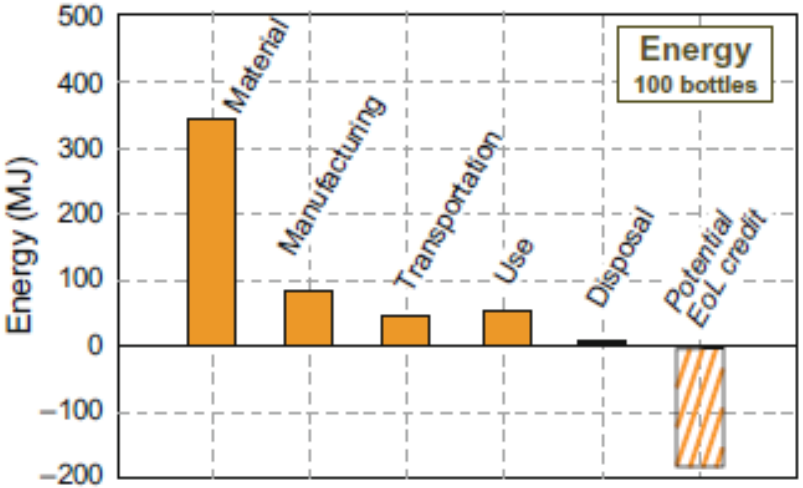
- Bottle, PET, molded, 4 kg
- Caps, PP, molded 0.1 kg
- 14 metric ton truck, 550 km
- Refrigerate 2 days
- Recycle



Data (Chs. 6 and 15)

- Embodied energy PET = 84 MJ/kg
- Embodied energy PP = 95 MJ/kg
- Energy, molding = 19 MJ/kg
- Energy, truck = 0.9 MJ/metric ton.km
- Refrigeration = 0.12 kW/m^3
- Recycling energy = 40 MJ/kg

Eco-audit



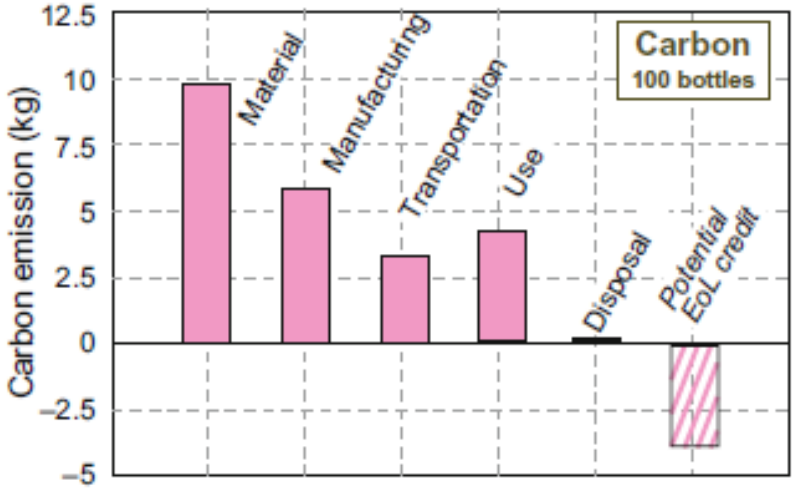


Table 7.1 The bill of materials and processes for 100 bottles

Component	Material	Process	Mass, *m* (kg)
Bottle	PET	Polymer molding	4.0
Cap	PP	Polymer molding	0.1
Dead weight (1 liter of water)	Water		100
		Total mass	104.1

Be careful at product functionality

	Material		Process	
Material	Energy, H_m (MJ/kg)*	CO_2 (kg/kg)*	Energy, H_p (MJ/kg)*	CO_2 (kg/kg)*
PET	85	2.35	19.5	1.48
PP	74	3.1	21	1.6

Multiplying the mass of each component by its primary shaping energy and summing give an estimate of the total processing energy—the second bar of

Materials Energy = $m_{PET} \times H_{m,PET} + m_{PP} \times H_{m,PP}$

Manufacturing Energy = $m_{PET} \times H_{p,PET} + m_{PP} \times H_{p,PP}$

H_p = energy for primary shaping

Same for CO_2

Life phase	Energy (MJ)	Energy (%)	CO_2 (kg)	CO_2 (%)
Material	348	66	9.6	43
Manufacture	80	15	6.1	27

Life phase	Energy (MJ)	Energy (%)	CO_2 (kg)	CO_2 (%)
Material	348	66	9.6	43
Manufacture	80	15	6.1	27
Transport	51	9	3.5	16
Use	62	10	3.0	14
Disposal	0.8	0	0.1	0
Totals, first life	524	100	22	100
Potential EoL credit	−188		−0.2	

Step 3, transportation. This step estimates the energy for transportation of the product from the manufacturing site to point of sale. For the water bottle, this is dominated by the transportation of the filled bottles from the French Alps to London, a distance of 550 km. The energy demands of transportation modes were described in Chapter 6 (Table 6.8); that for the 14-metric-ton truck used in this example is 0.9 MJ/metric ton · km. Multiplying this by the mass of the product and the distance travelled provides the estimate. It is not just the bottles that travel 550 km but also the water they contain. This is included in the bill of materials shown in

Table 6.9 The approximate energy and carbon footprint of transportation*

Transportation type and fuel	Energy (MJ/metric ton · km^{+})	Carbon footprint (kg CO_2/metric ton · km^{+})
Ocean shipping—Diesel	0.16	0.015
Coastal shipping—Diesel	0.27	0.019
Barge—Diesel	0.36	0.028
Rail—Diesel	0.25	0.019
Articulated HGV (up to 55 metric tons)—Diesel	0.71	0.05
40 metric ton truck—Diesel	0.82	0.06
32 metric ton truck—Diesel	0.94	0.067
14 metric ton truck—Diesel	1.5	0.11
Light goods vehicle—Diesel	2.5	0.18
Family car—Diesel	1.4–2.0	0.1–0.14
Family car—Gasoline	2.2–3.0	0.14–0.19
Family car—LPG	3.9	0.18
Family car—Hybrid gasoline-electric	1.55	0.10
Super sports car and SUV—Gasoline	4.8	0.31
Long haul aircraft—Kerosene	6.5	0.45
Short haul aircraft—Kerosene	11–15	0.76
Helicopter (Eurocopter AS 350)—Kerosene	55	3.30

Distance as key factor

First, simple lesson: Reduce the distance between production site and customer of any good

Time (t) is not considered

One could prefer a less efficient transportation, in terms of energy, but faster

Trade-off analysis could be applied

$E^* = E + \alpha t$

Or we could think at normalizing E by t

$E^* = E/t$

Using transport data

Example: Cars manufactured in China are shipped 19,000 km to Europe where they are transported 500 km by a 32-metric ton truck to the point of sale. If the car weighs 1,400 kg, how much energy is used in this transport cycle?

Answer: From Table 6.9 the energy required for ocean shipping is 0.16 MJ/metric ton · km and that for a 32-metric ton truck is 0.46 MJ/metric ton · km. Thus the energy of the transport cycle is

$$1.4(19,000 \times 0.16 + 500 \times 0.46) = 4,578 \text{ MJ}$$

Transportation impact = sum of (many) contributions

Step 4, the use phase. The use phase requires a little explanation. There are two different classes of contributions.

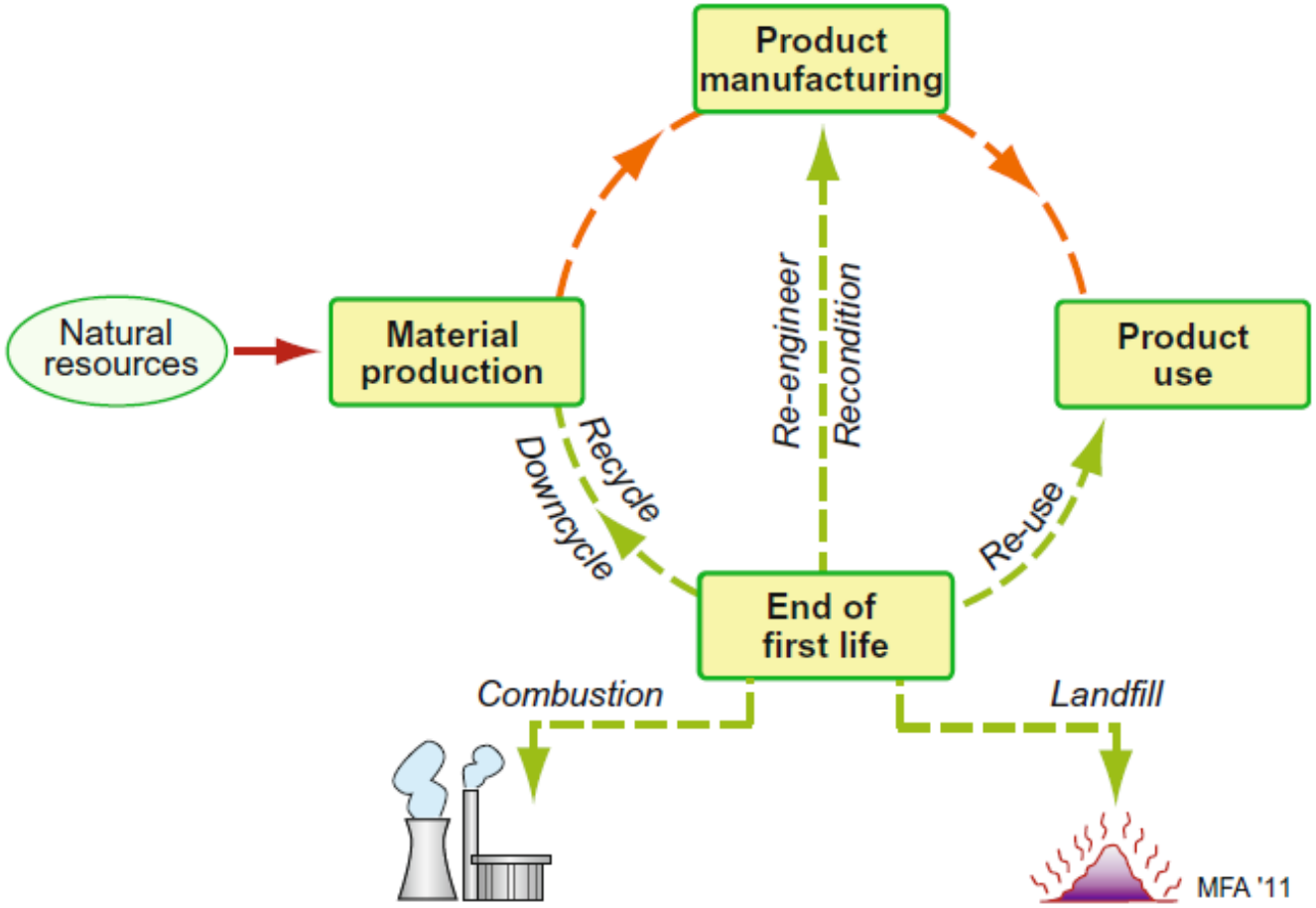
- Some products are (normally) static but require energy to perform their function: electrically powered products like hairdryers, electric kettles, refrigerators, power tools, and space heaters are examples. Even apparently nonpowered products like household furnishings or unheated buildings still consume some energy in cleaning, lighting, and maintenance. The first class of contribution, then, relates to the power consumed by, or on behalf of, the product itself. **Static mode**
- The second class is associated with transportation. Products that form part of, or are carried by, a transportation system add to its mass and thereby augment its energy consumption and CO_2 burden. The transportation table, Table 6.8, lists the energy and CO_2 penalty per unit weight and distance. Multiplying this by the product weight and the distance over which it is carried gives an estimate of the associated use-phase energy and CO_2. **Dynamic mode**

Static mode analysis

The PET bottle is a static product. Energy is consumed on its behalf via refrigeration for 2 days. The power requirements for refrigeration, based on A-rated appliances, are 0.12 kW/m^3 for refrigeration at 4°C and 0.15 kW/m^3 for freezing at −5°C, using electrical power in both cases. Thus refrigerating 1 m^3 for 2 days takes 5.76 kWh. Converting this to MJ/m^3 by multiplying by 3.6, and to an oil-equivalent energy by dividing by an energy-conversion efficiency of 33%, gives 62 MJ/m^3. One bottle requires about 0.01 m^3 of refrigerator space, so the energy to refrigerate it for 2 days is a surprising 0.6 MJ per bottle—more than the energy to truck it from France.

Step 5, disposal. There are five options for disposal at the end of life: *landfill, combustion for energy recovery, recycling, re-engineering,* and *reuse* (look back at Figure 4.2). A product at end of first life has the ability to return part or all of its embodied energy. This at first sounds wrong—much of the "embodied" energy was not *embodied* at all but was lost as low-grade heat via the inefficiencies of the processing plant, and even when it is still there, it is, for metals and ceramics, inaccessible since the only easy way to recover energy directly is by combustion, not an option for steel, concrete, or brick. But think of it another way. If the materials of the product are recycled or the product itself is re-engineered or reused, a need is filled without drawing on virgin material, thereby saving energy. Carbon release works in the same way, with one little twist: one end-of-life option, combustion, recovers some energy but in doing so it releases CO_2.

Re-engineering or refurbishment. There is the story of the axe—an excellent axe—that, over time, had two new heads and three new handles. But it was still the same axe. Refurbishment, for some products, is cost-effective and, compared with total replacement, energy efficient. Aircraft, for instance, don't wear out; instead, replacement of critical parts at regular inspection periods keeps the plane, like the axe, functioning just as it did when it was new. The Douglas DC3, a 70-year-old design, is still flying, though not, of course, in the hands of its original owner. Premium airlines fly premium aircraft, so older models are sold on to operators with smaller budgets.



Disposal route	First-order estimate for energy (MJ/kg)	First-order estimate for carbon (kg/kg)
1. **Landfill.** Collect and transport to landfill site.	EoL debit $H_d \approx 0.1$	EoL debit $C_d \approx 0.01$
2. **Combust for heat recovery.** Collect, combust, recover heat.	EoL credit $\eta_c H_c$ (η_c = combustion efficiency = 0.25 H_c = heat of combustion)	EoL debit $C_c = \alpha H_c$ (C_c = combustion carbon $\alpha = 0.07$ kg CO_2 /MJ)
3. **Recycle.** Collect, sort by material family and class, recycle.	$\tilde{H} + (1-r)H_d$ EoL credit $r(\tilde{H} - H_{rc})$	$\tilde{C} + (1-r)C_d$ EoL credit $r(\tilde{C} - C_{rc})$
4. **Re-engineer.** Collect, dismantle, replace or upgrade components, re-assemble.	Recover most of embodied energy H_m. Use $0.9\tilde{H}$ as EoL credit.	Recover most of carbon footprint C_m. Use $0.9\tilde{C}$ as EoL credit.
5. **Reuse.** Market as "pre-owned" product via trading outlets, websites etc.	Recover mean embodied energy $\tilde{H}$ as EoL credit	Recover mean carbon footprint $\tilde{C}$ as EoL credit

*We define the effective embodied energy $\tilde{H}$ and carbon footprint $\tilde{C}$ as

$$\tilde{H} = RH_{rc} + (1-R)H_m \text{ MJ/kg} \quad \text{and} \quad \tilde{C} = RC_{rc} + (1-R)C_m \text{ kg/kg}$$

H_{rc}, C_{rc} = contributions from recycled material with the same value than the virgin one

$$\tilde{H} = RH_{rc} + (1 - R)H_m \text{ MJ/kg}$$

Credit = $\tilde{H}$ - H_m = [R H_{rc} + H_m – R H_m] – H_m = R (H_m-H_{rc})

Material and process step: aluminum alloy connecting rod	**Energy**	**Units**
Embodied energy (Ch.15)	210	MJ/kg
Embodied energy, recycling (Ch. 15)	25	MJ/kg

The estimated energy recovered by recycling is

$$210 - 25 = 185 \text{ MJ/kg}$$

Thus the energy "credit" from recycling the machined metal is

$$1.8 \times 184 = 331 \text{ MJ}$$

This reduces the total energy demand of the machined-from-solid connecting rod to 722 MJ, barely more than that of the cast connecting rod.

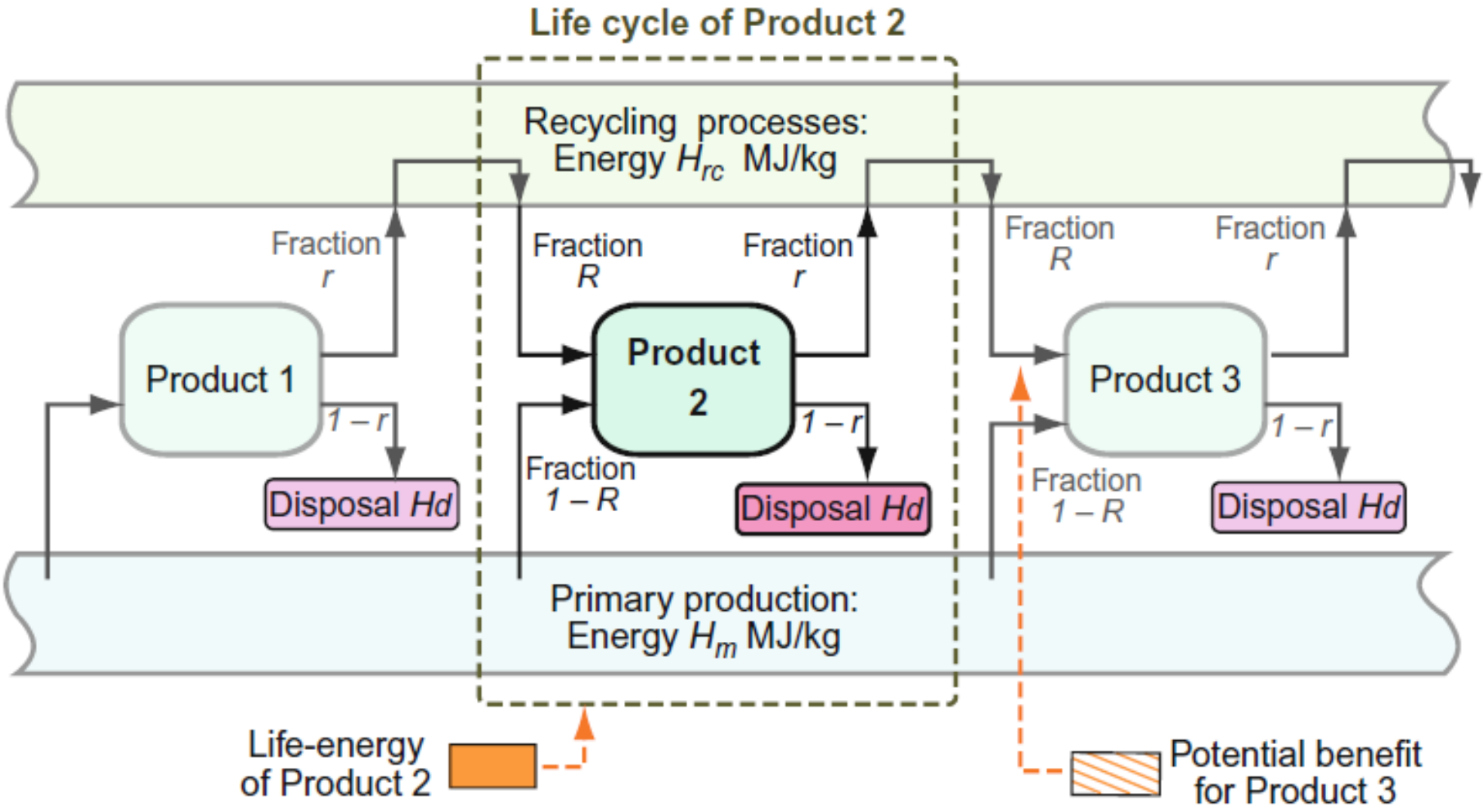
Table 7.5 Recycle energy and CO_2 and heats of combustion for PET and PP

Material	Embodied energy H_m MJ/kg*	Material $CO_{2,eq}$ C_m kg/kg*	Recycle energy H_{rc} MJ/kg*	Recycle $CO_{2,eq}$ C_{rc} kg/kg*
PET	85	2.35	39	2.3
PP	74	3.1	50	2.1

**From the data sheets of Chapter 15.*

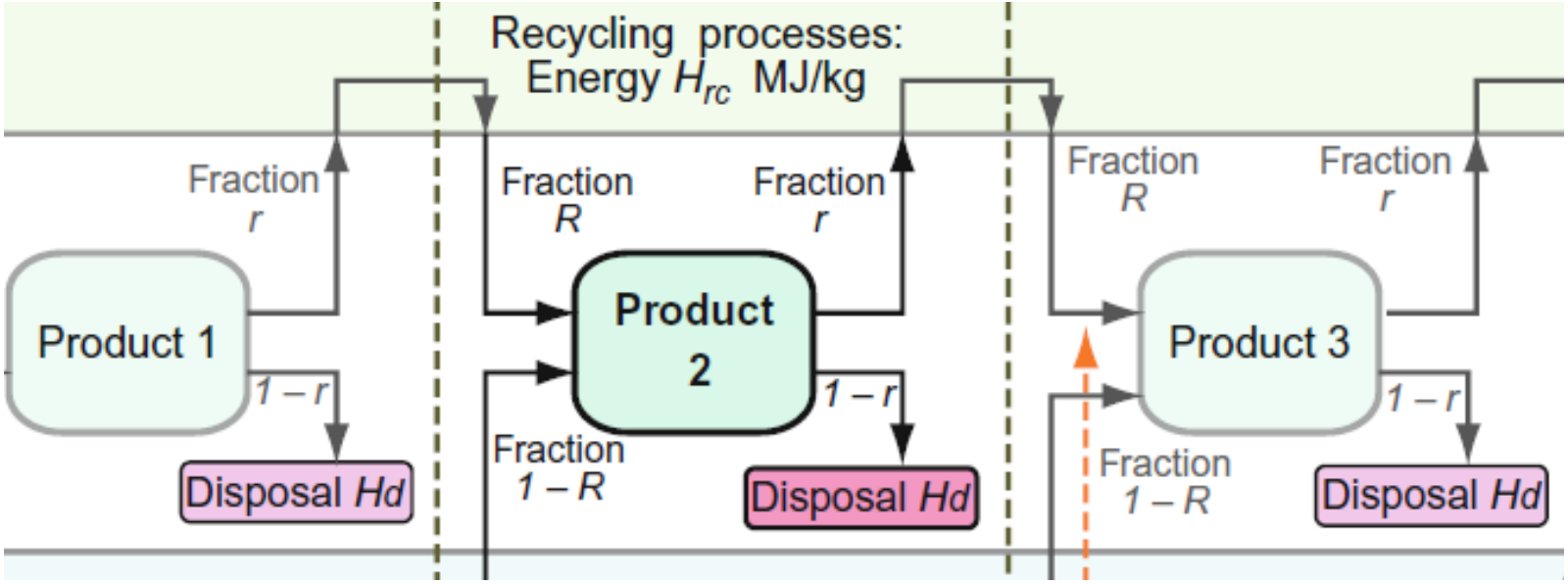
Attention to product chains

Typical of open-loop recycling (Product 1, 2, 3, … are different)



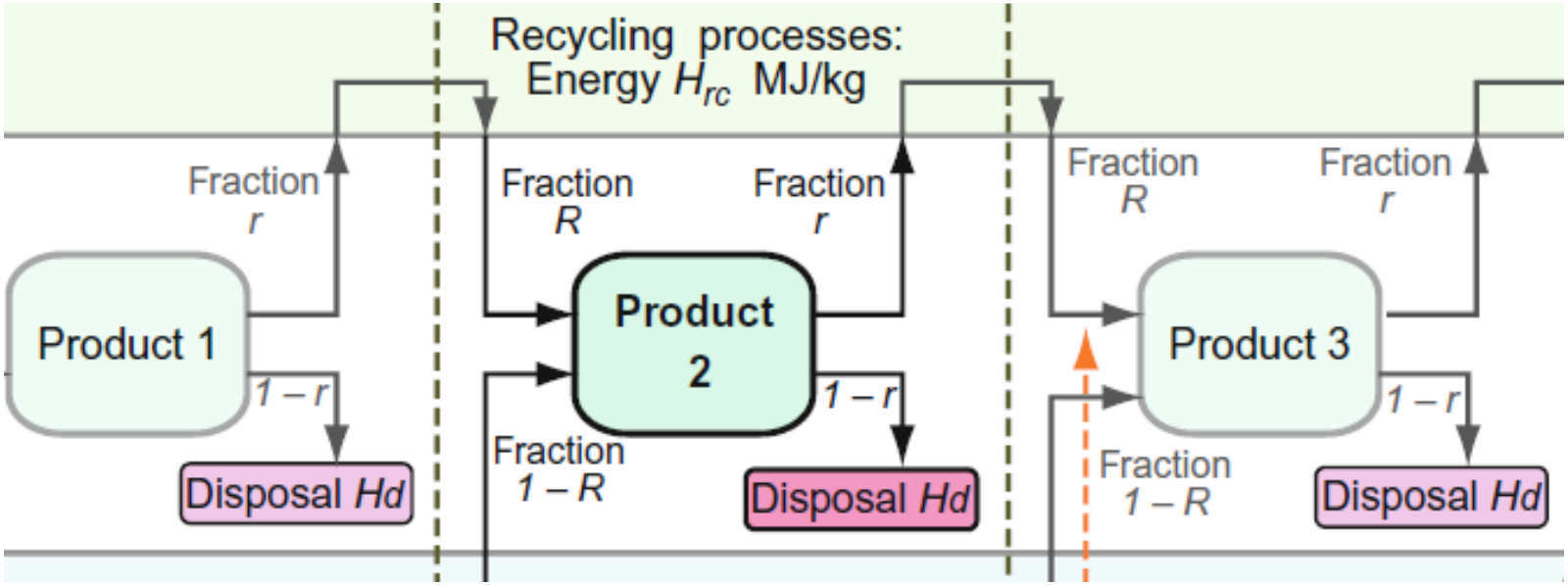
Attention to the balance between credits and debits

Allocation models needed: *recycled content method*, *substitution method*



There are two methods for dealing with this allocation problem. The *recycled content method* gives Product 2 the full credit for recycled content at the start of life but none for recycling at life's end. We model it here for energy; the modeling for emissions follows the same path. Product 2 uses a fraction R of recycled materials with an embodied energy H_{rc} per kg supplemented by a fraction $(1 - R)$ of virgin materials with embodied energy H_m per kg. At the end of life a fraction r is (or could be) recycled, but Product 2 gets no credit for that. It must, however, accept a small penalty for the fraction $(1 - r)$ that must be disposed of at end of life, costing a disposal energy H_d per kg. The net embodied energy H_{net} per kg of material is then

$$(H_{net})_{recycle\ content} = R\,H_{rc} + (1 - R)H_m + (1 - r)H_d \qquad (7.1)$$



The alternative (the *substitution method*) is to award the full benefit of recycling at the end of life, $r(H_m - H_{rc})$, to Product 2 but give it no credit for recycled content at the start of life, giving the net embodied energy H_{net} per kg of material as

$$(H_{net})_{substitution} = H_m - r\,(H_m - H_{rc}) + (1 - r)H_d = rH_r + (1 - r)(H_m + H_d) \qquad (7.2)$$

Identical results for r = R

Ashby = focus on *present* resources, recycled content method preferred for calculations of life-cycle energy and carbon emission