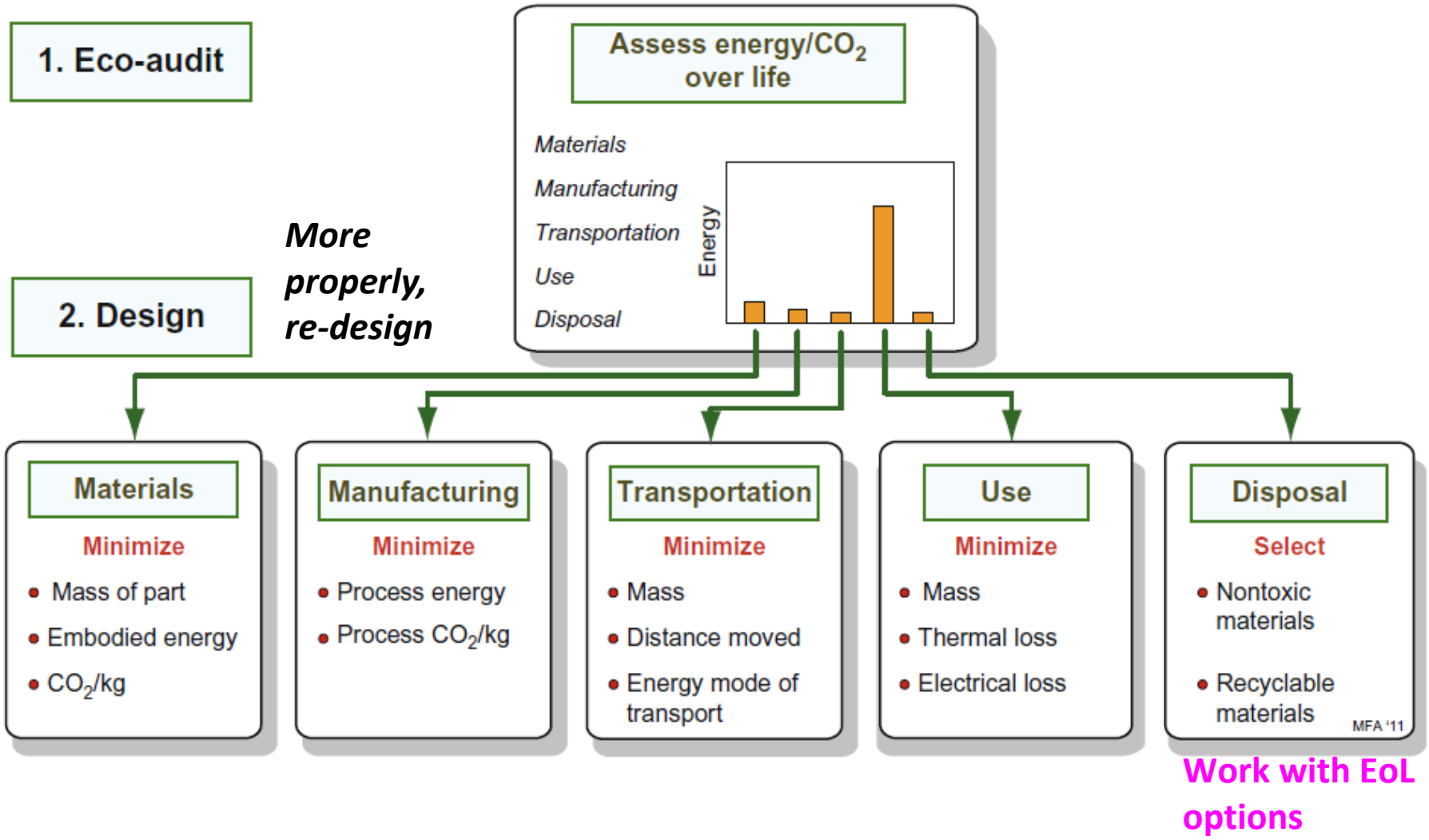
1. Eco-audit
Assess energy/CO_2 over life
Materials
Manufacturing
Transportation
Use
Disposal
Energy
2. Design
More properly, re-design
Materials
Minimize
Mass of part
Embodied energy
CO_2/kg
Manufacturing
Minimize
Process energy
Process CO_2/kg
Transportation
Minimize
Mass
Distance moved
Energy mode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

Eco-sustainability of reuse

Reusable vs. Disposable cups



Disposable, ***Polypropylene***
[http./lwww.twenga.it/bicchieri-polipropilene.html];



Reusable, ***Polycarbonate***
[www.amazon.it]

Attribute	Disposable	Reusable
Material	Polypropylene	Polycarbonate
Mass of 1,000 cups (kg)	16	113
Shaping process	Molding	Molding
Mass of cardboard packaging for 1,000 cups (kg)	0.6	2.3
Electrical energy for single wash of 1,000 cups (kWh)	—	20

Eco-sustainability of reuse

Reusable vs. Disposable cups



Disposable, ***Polypropylene***
[http./lwww.twenga.it/bicchieri-polipropilene.html];



Reusable, ***Polycarbonate***
[www.amazon.it]

Attribute	Polypropylene	Polycarbonate	Cardboard
Embodied energy, virgin material (MJ/kg)*	95	110	28
Carbon footprint, virgin material $CO_{2,equiv}$ (kg/kg)*	2.7	5.6	1.4
Molding energy (MJ/kg)*	21	18.5	—
Molding carbon footprint, $CO_{2,equiv}$ (kg/kg)*	1.6	1.4	—
Oil-equiv. energy for single wash, 1,000 cups (MJ)	—	195	—

Eco-sustainability of reuse

Energy for forming operations

$$E_{disposable} = m_{Cups\ in\ PP} \cdot \left(H_{p,PP} + H_{form,PP}\right) + m_{Cardboard\ packaging\ for\ PP} \cdot \left(H_{p,Cardboard}\right)$$

$$E_{disposable} = 16\ kg \cdot \left(95\frac{MJ}{kg} + 21\frac{MJ}{kg}\right) + 0.6 \cdot \left(28\frac{MJ}{kg}\right) = \mathbf{1873\ MJ}$$

$$E_{reusable} = m_{Cups\ in\ PC} \cdot \left(H_{p,PC} + H_{form,PC}\right) + m_{Cardboard\ packaging\ for\ PC} \cdot \left(H_{p,Cardboard}\right)$$

$$E_{reusable} = 113\ kg \cdot \left(110\frac{MJ}{kg} + 18.5\frac{MJ}{kg}\right) + 2.3 \cdot \left(28\frac{MJ}{kg}\right) = \mathbf{14585\ MJ}$$

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Embodied energy, virgin material (MJ/kg)*	95	110	28
Carbon footprint, virgin material $CO_{2,equiv}$ (kg/kg)*	2.7	5.6	1.4
Molding energy (MJ/kg)*	21	18.5	—
Molding carbon footprint, $CO_{2,equiv}$ (kg/kg)*	1.6	1.4	—
Oil-equiv. energy for single wash, 1,000 cups (MJ)	—	195	—

Eco-sustainability of reuse

$$N \cdot E_{disposable} > E_{reusable} + (N-1) \cdot E_{washing}$$

$$N \cdot 1873\ MJ > 14585\ MJ + (N-1) \cdot 195\ MJ$$

Above a certain threshold (=number N of uses) disposable cups are no longer sustainable

Below the threshold, disposable cups ARE sustainable

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Embodied energy, virgin material (MJ/kg)*	95	110	28
Carbon footprint, virgin material $CO_{2,equiv}$ (kg/kg)*	2.7	5.6	1.4
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Eco-sustainability of reuse

$$N \cdot E_{disposable} > E_{reusable} + (N-1) \cdot E_{washing}$$

$$N \cdot 1873\ MJ > 14585\ MJ + (N-1) \cdot 195\ MJ$$

Above a certain threshold (=number N of uses) disposable cups are no longer sustainable

Below the threshold, disposable cups ARE sustainable

- **Reuse theoretically sustainable for N=9**
- **We should actually consider two thresholds, for energy ($N=N_E$) and for carbon dioxide emissions (N_{CO2}): the actual threshold will be $N^*=\max(N_E, N_{CO2})$**
- **The threshold is calculated neglecting factors that would increase it significantly (e.g. limited numbers of cups effectively returned, damaged cups etc.)**
- **EoL credits, from recycling**, may promote PP



Break-even number

Number of times at which a reusable solution becomes more sustainable

Emission PE non reusable x 19 = Emission Juco

Juco saves emissions if reused >19 times

7 x 2.1 x 19 = 257 x 1.1

A reusable solution is not always a valid solution

Carrier bags. The lightest weighs 7 grams, the heaviest weighs 257 grams.

Bag	Material	Mass (g)	Material CO_2 footprint (MJ/kg)*	CO_2 footprint, 100 bags (kg)	How many reuses?
1	Polyethylene (PE)	7	2.1	1.5	1
2	Polyethylene (PE)	20	2.1	4.3	3
3	Paper	46	1.4	6.4	5
4	Paper	54	1.4	7.6	6
5	Polypropylene (PP)	75	2.7	20.3	14
6	Juco-75% jute 25% cotton	257	1.1	28.3	19

Eco-sustainability of reuse

Grocery bags ('shoppers')

Material	Mass per bag (g)	CFP CO_2 Footprint kg per product (kg/kg)
Polyethylene (PE)	7	2.1
Polyethylene (PE)	20	2.1
Paper	46	1.4
Paper	54	1.4
Polypropylene (PP)	75	2.7
Juco-75% jute 25% cotton	257	1.1

Eco-sustainability of reuse

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Eco-sustainability of reuse

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Polyethylene (PE)	7	1.5
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Paper	46	6.4
Paper	54	7.6
Polypropylene (PP)	75	20.3
Juco-75% jute 25% cotton	257	28.3

Eco-sustainability of reuse

Grocery bags ('shoppers')

Quite surprising result… the mass is the key point

Material	Mass per bag (g)		CFP CO_2 Footprint For 100 bags (kg)
Polyethylene (PE)	7	Benchmark	1.5
Polyethylene (PE)	20		4.3
Paper	46		6.4
Paper	54		7.6
Polypropylene (PP)	75		20.3
Juco-75% jute 25% cotton	257		28.3

Eco-sustainability of reuse

Grocery bags ('shoppers')

Threshold values

	CFP (kg)	Number of reuses for sustainability against PE
Polyethylene (PE)	1.5	1
Polyethylene (PE)	4.3	3
Paper	6.4	5
Paper	7.6	6
Polypropylene (PP)	20.3	14
Juco-75% jute 25%	28.3	**19**

$$19 * CFP_{PE} = 28.5\ kg > CFP_{Juco\text{-}jute}$$

Eco-sustainability of reuse

Grocery bags ('shoppers')

Threshold values
Attention to the benchmark

	CFP (kg)		Number of reuses for sustainability against PE
~~Polyethylene (PE)~~	~~1.5~~		~~1~~
Polyethylene (PE)	4.3	**New benchmark**	3
Paper	6.4		5
Paper	7.6		6
Polypropylene (PP)	20.3		14
Juco-75% jute 25%	28.3		**19**

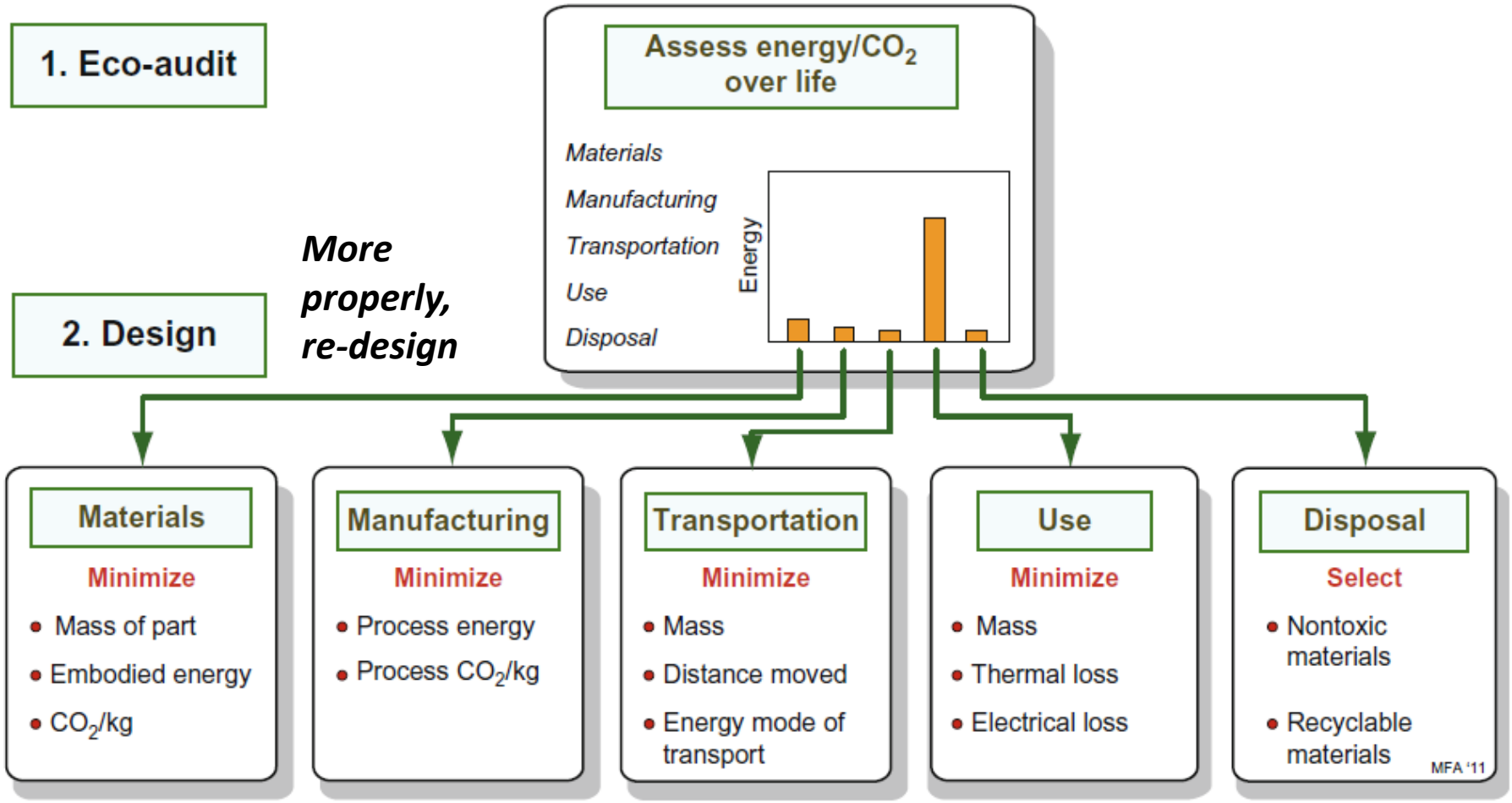
Eco-sustainability of reuse

Grocery bags ('shoppers')

Threshold values

	CFP (kg)		Number of reuses for sustainability against PE_{new}
~~Polyethylene (PE)~~	~~1.5~~		~~1~~
Polyethylene (PE)	4.3	New benchmark	1
Paper	6.4		2
Paper	7.6		2
Polypropylene (PP)	20.3		5
Juco-75% jute 25%	28.3		7

$$7 * CFP_{PE\ new} = 30.1\ kg > CFP_{Juco\text{-}jute}$$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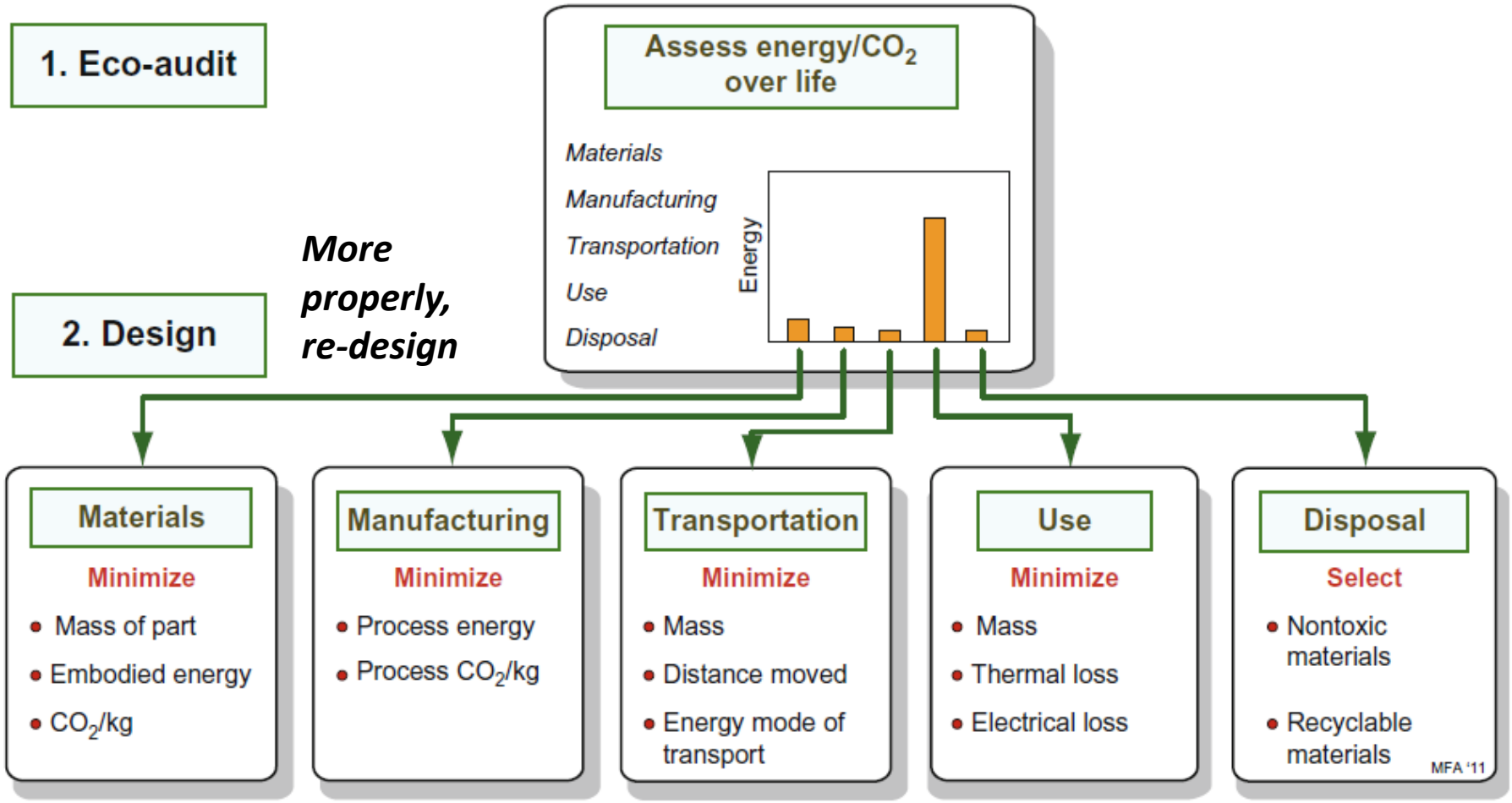
Transportation
Minimize
Mass
Distance moved
Energy mode of transport
Use
Minimize
Mass
Thermal loss
Electrical loss
Disposal
Select
Nontoxic materials
Recyclable materials
MFA '11



What happens if process is not negligible?
Typically when different material classes are considered



$$M = \frac{E^{1/2}}{H_p \rho}$$

$$M = \frac{\sigma_f^{2/3}}{H_p \rho}$$

Good but expressing just materials contribution (=primary preparation phase)

Design requirements for the containers

Function	Container for cold drink
Constraints	Must be recyclable
Objective	Minimize production energy per unit capacity
Free variables	Choice of material

Details of the containers

Container type	Material	Mass (g)	Mass/liter (g)	Energy/liter (MJ/l)
PET 400 ml bottle	PET	25	62	5.4
PE 1 milk bottle	High density PE	38	38	3.2
Glass 750 ml bottle	Soda glass	325	433	8.2
Al 440 ml can	5000 series Al alloy	20	45	9.0
Steel 440 ml can	Plain carbon steel	45	102	**2.4**

Details of the containers

Container type	Material	Mass (g)	Mass/liter (g)	Energy/liter (MJ/l)
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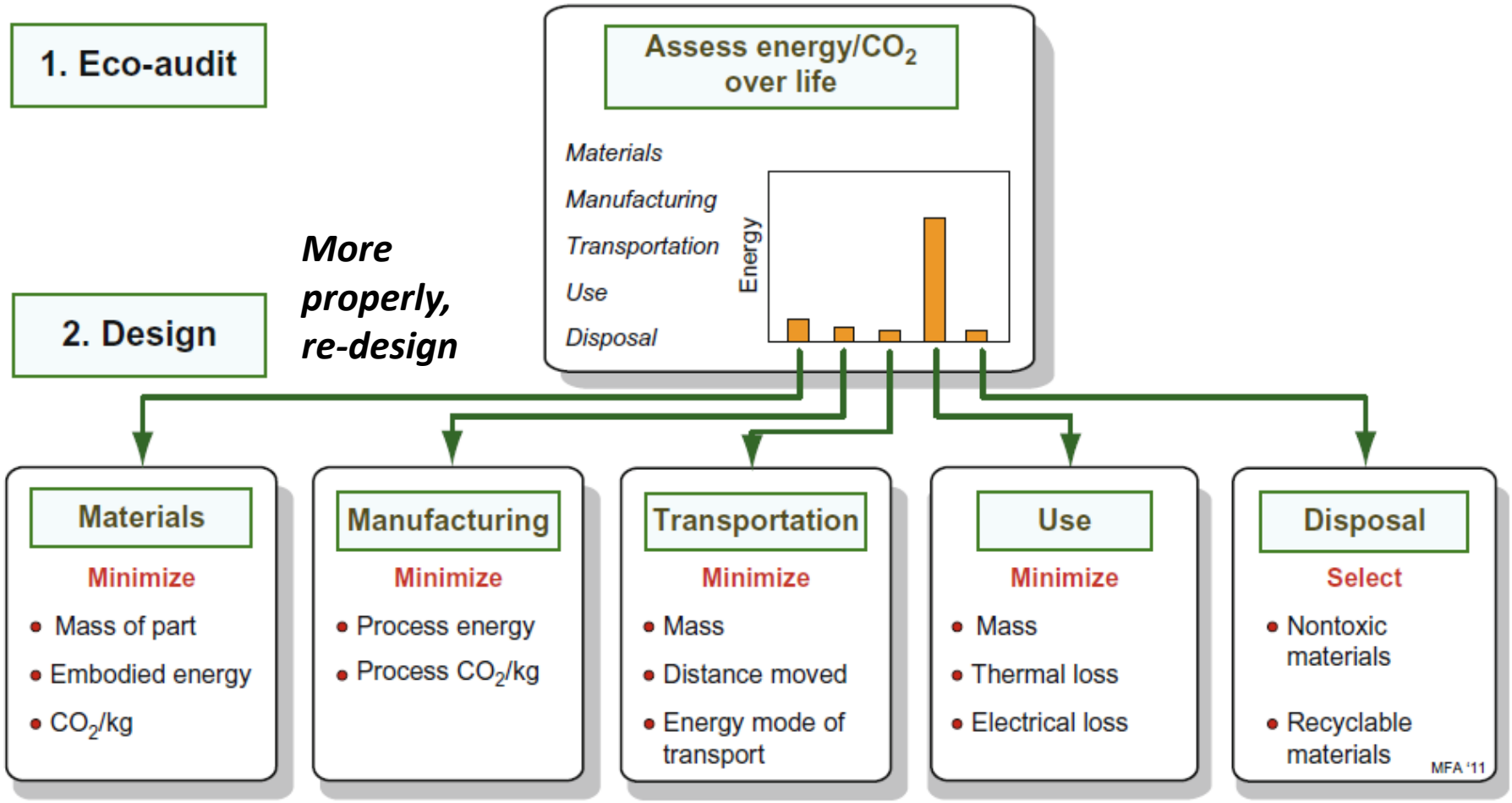
Glass 750 ml bottle	Soda glass	325	433	8.2
Al 440 ml can	5000 series Al alloy	20	45	9.0
Steel 440 ml can	Plain carbon steel	45	102	**2.4**

Different materials needing different processing methods AND/OR energies [e.g. polymer molding not comparable to glass molding]

Data for the materials of the containers (from Appendix C)

Material	Production energy MJ/kg	Forming method	Forming energy MJ/kg
PET	84	Molding	3.1
PE	80	Molding	3.1
Soda glass	14	Molding	4.9
5000 series Al alloy	200	Deep drawing	0.13
Plain carbon steel	23	Deep drawing	0.15



Materials & Use combined?
Trade-off approach as solution
1st case: numerical approach

Another example: vehicles

Table 9.7 Exchange constants α_m for the mass–cost trade-off for transport systems

Sector: transport systems	Basis of estimate	Exchange constant, α_m (US$/kg)
Family car	Fuel saving	1–2
Truck	Payload	5–20
Civil aircraft	Payload	100–500
Military aircraft	Payload, performance	500–1,000
Space vehicle	Payload	3,000–10,000

Using penalty functions

Example (1): The exchange constant for weight savings in a light goods vehicle is $\alpha_m = \$12/\text{kg}$, meaning that the value of weight reduction over the life of the vehicle is \$12 for each kilogram saved. A maker of such vehicles offers three models. The first uses steel panels for the body work. The second uses aluminum, costs \$2,500 more, but weighs 300 kg less. The third offers carbon-fiber paneling, costs \$8,000 more and weighs 500 kg less. Which is the best buy?

Answer: The penalty functions for the steel (1) and aluminum (2) vehicles are

$$Z_1 = C_1 + \alpha_m m_1$$

and

$$Z_2 = C_2 + \alpha_m m_2$$

The aluminum vehicle is attractive only if its value of Z is lower than that of the steel one. Writing

$$\begin{aligned}\Delta Z = Z_2 - Z_1 &= C_2 - C_1 + \alpha_m(m_2 - m_1) \\ &= 2{,}500 - 12 \times 300 = -\$\,1{,}100\end{aligned}$$

The aluminum-paneled vehicle offers a life saving of \$1,100—it is a good buy. Repeating the comparison for the composite-paneled vehicle gives a value of $\Delta Z = +\$2{,}000$. It is not a good buy. **Composites also disputable for recycling**



USING MORE SUSTAINABLE MATERIALS

Using more sustainable materials is a major long term goal for us as a responsible business.

The planet's resources are dwindling. Choosing and using materials responsibly will not only benefit our environment, it will also help us tackle future price fluctuations as demand for these precious resources increases.

Recycled Aluminium

The amount of recycled aluminium we use in our vehicles continues to rise. We work in partnership with the REAL CAR initiative who develop ways to employ recycled aluminium in our products.

Together we have identified a method of re-melting scrap aluminium generated in our own presses with those of our principle suppliers into a high-grade sheet metal alloy. Both the latest Jaguar XJ and the All New Range Rover feature recycled aluminium sheets.

We also now have a closed loop waste recovery and recycling system at our Castle Bromwich Jaguar production centre, as well as a trial process at Solihull, where Land Rover's new all-aluminium models (The Range Rover and Range Rover Sport) are manufactured.

Switching to Organic Materials

Beyond the main car body, there are even wider opportunities to make responsible choices. We are reducing our use of synthetics and plastics by looking at more organic materials such as leather and natural rubber. (A key feature of the new Range Rover – whose leather interiors were sourced from Bridge of Weir in Scotland). Wood too, can be sourced responsibly from a sustainably managed forest to make stylish, premium interiors for our vehicles.

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Using More Sustainable Materials in the All New Range Rover

READ MORE

web JAGUAR: THE STORY OF ALUMINIUM

web THE ALL NEW RANGE ROVER

http://www.jaguarlandrover.com/



DESIGNING FOR FUEL EFFICIENCY

Typically, over 70% of a vehicle's lifetime carbon footprint will come from the fuel it uses, when driven. Designing fuel efficient vehicles is therefore key to reducing our impact on the environment, as well as delivering cost savings for customers.

We are aiming to reduce our fleet tailpipe emissions by 25% by 2015.This calls for fresh thinking at the product design stage. Analysing engine performance, aerodynamics and more to inspire new ways to drive down emissions.

Our approach focuses on four key areas:

1. Lightweight Body Structures

Jaguar pioneered the use of **lightweight, aluminium body structures**. More lightweight and malleable materials not only offer improved aerodynamics, they also reduce the size of the engines required to deliver power.

2. Hybrid & Electric Solutions

We have a team of 260 engineers exploring how internal combustion engines can work with electric motors as well as ways in which vehicles can recover the energy they lose in braking and driving. This work has led to the **launch of our Range Rover Sport Hybrid** - the world's first hybrid luxury SUV. With CO_2 emissions as low as 169g/km and 44 miles per gallon, emissions from the Range Rover Sport Hybrid are 26% lower than the standard diesel model.

3. Stop/Start Technology

This kind of **intelligent technology** offers significant fuel saving opportunities. In the All New Range Rover, the system shuts down the engine in just 300 milliseconds when the vehicle comes to rest, then restarts as the driver's foot leaves the brake pedal – reducing fuel consumption and CO_2 by between 5% to 7%.

4. Powertrain Efficiency

Advances in powertrain efficiency are helping us create engines that deliver high performance with fewer emissions.

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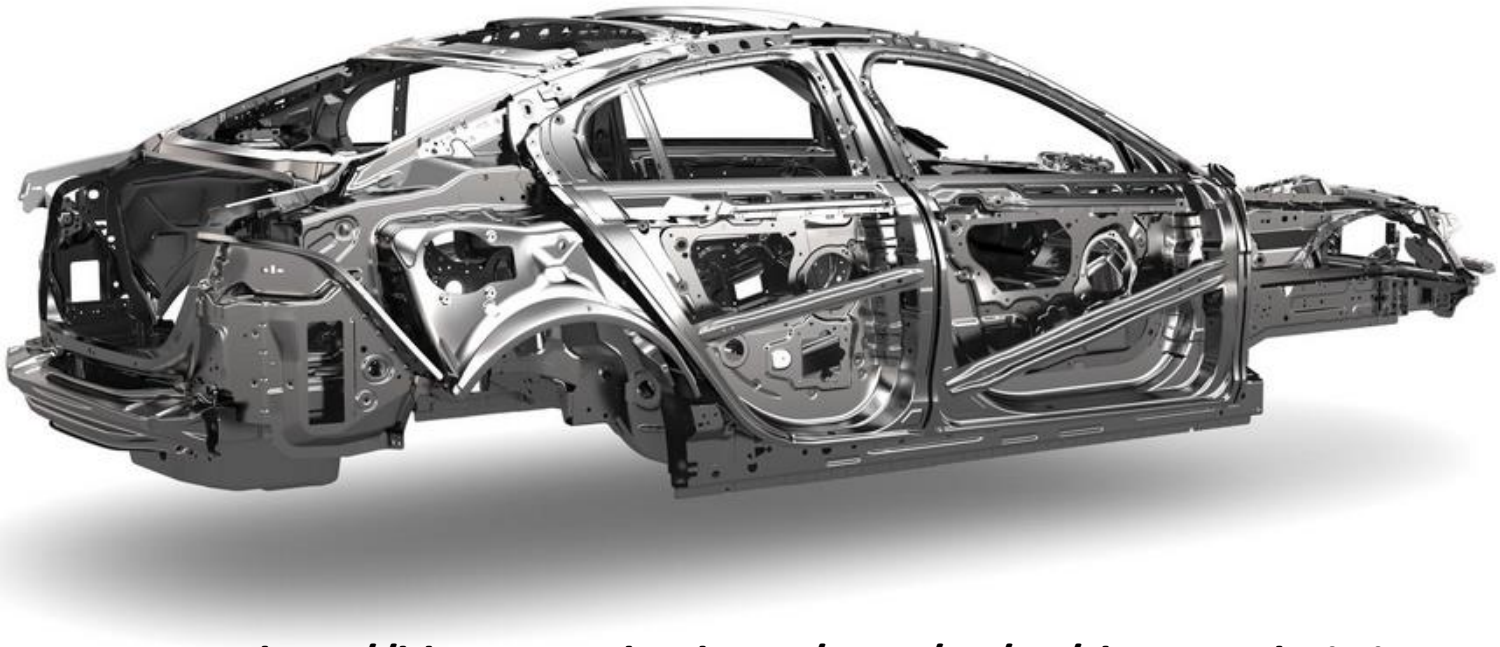
Efficient Technologies

READ MORE

- JAGUAR ANNOUNCES ALL-NEW TECHNICALLY ADVANCED ALUMINIUM ARCHITECTURE AND REVEALS C-X17 SPORTS CROSSOVER CONCEPT
- LAND ROVER LAUNCHES ITS FIRST HYBRID RANGE ROVER MODELS
- ALL-NEW RANGE ROVER OFFERS INCREASED POWERTRAIN CHOICE WITH ADVANCED SUPERCHARGED V6 PETROL ENGINE
- JAGUAR EXPANDS POWERTRAIN CHOICE
- JAGUAR LAND ROVER ANNOUNCES ADVANCED POWERTRAIN RESEARCH PROJECT TO PUSH BOUNDARIES OF HYBRID AND BATTERY-ELECTRIC VEHICLE TECHNOLOGY

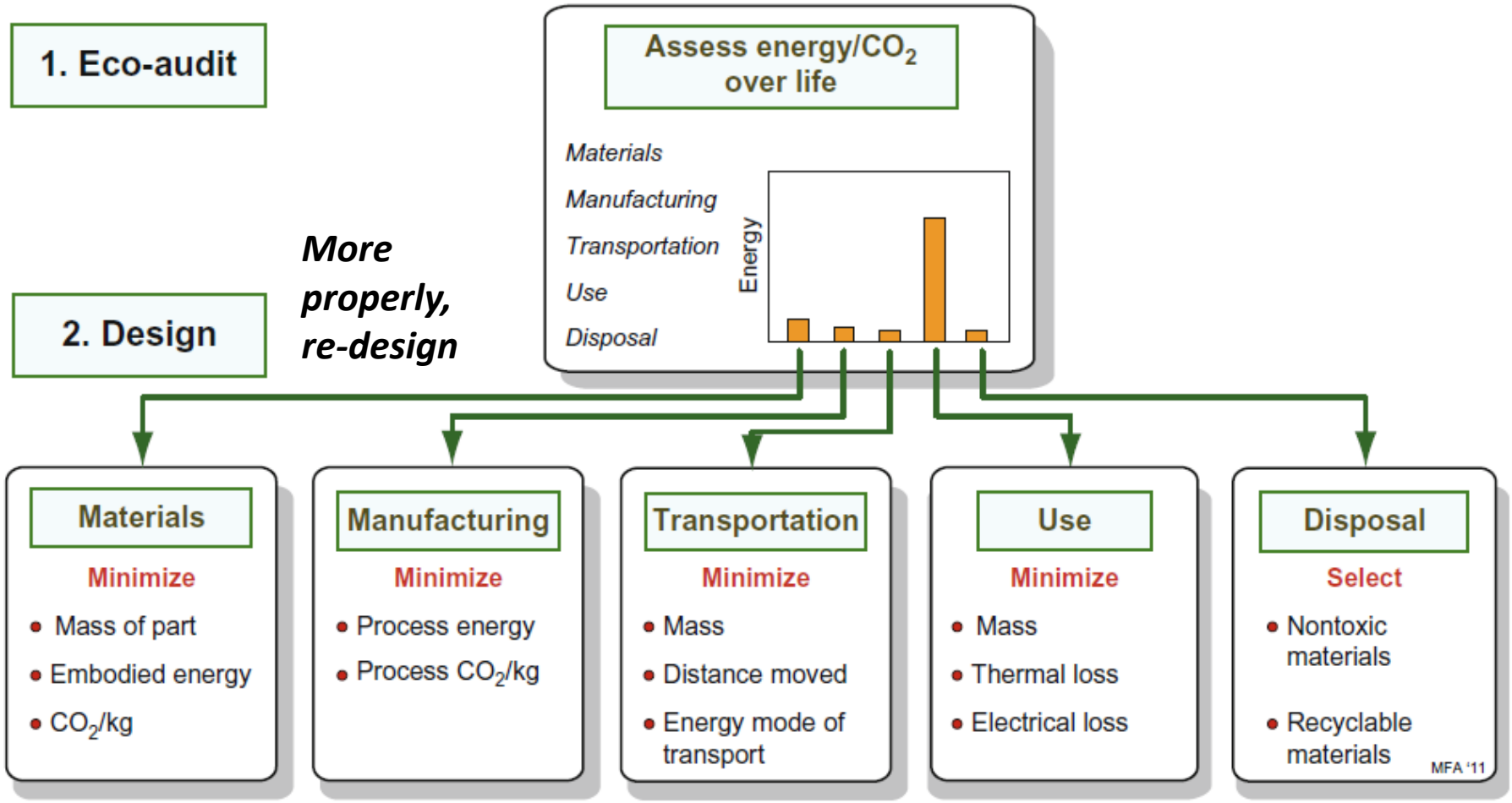


http://blogs.youwheel.com/2015/02/10/short-analysis-jaguars-advantages/

Aluminum favoured also by recyclability

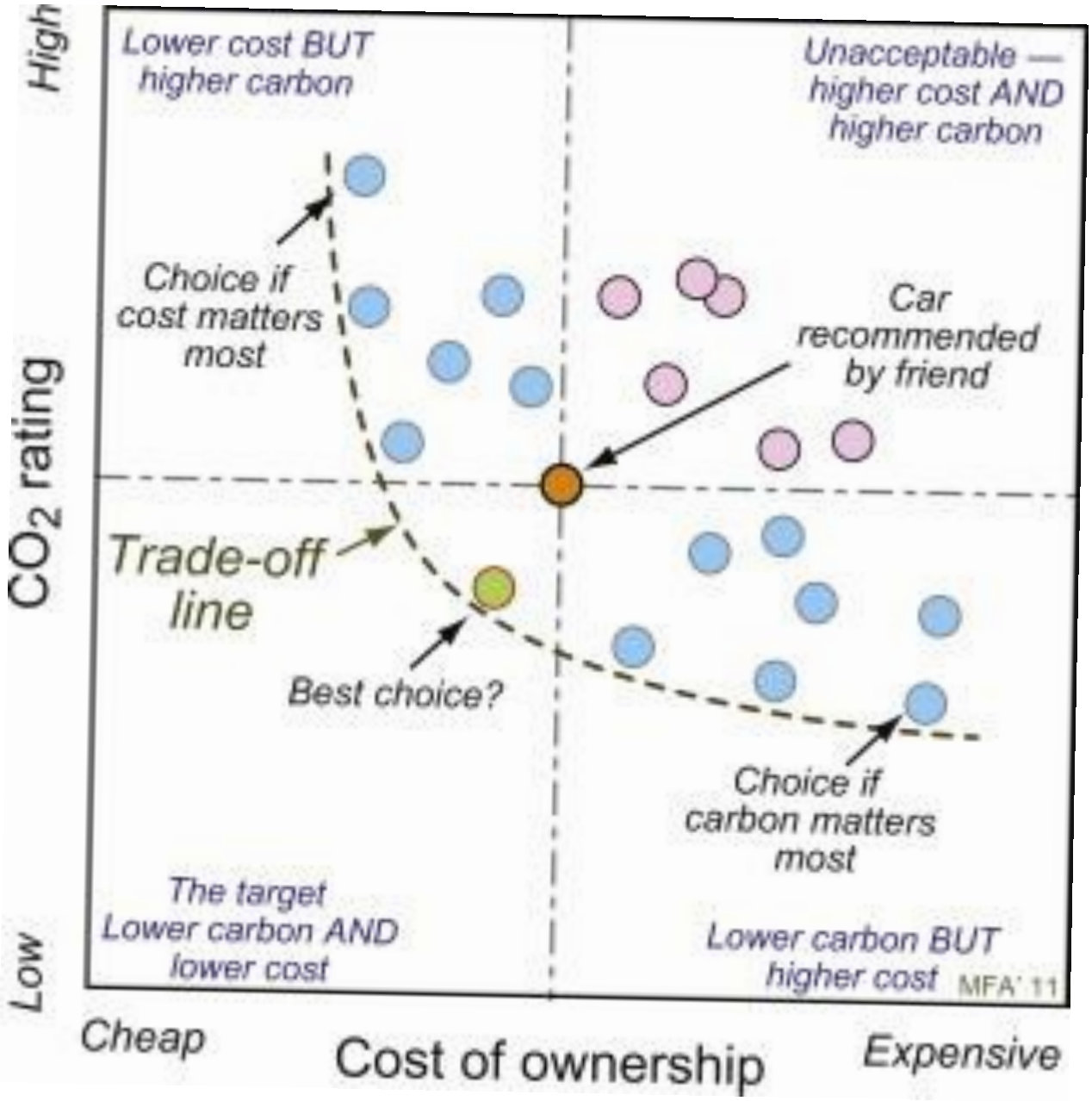
(Above: Jaguar XE's aluminum body-in-white)

1. **Aluminum car body structure across the full product line**. Almost all Jaguar models are using full aluminum unibody construction (*aluminum monocoque*). Starting from 2003, the XJ has been full aluminum for two generations (X350, X358, X351); The latest XK and F-Type are also full aluminum. The cheapest XE also has a car body composed of 75% aluminum. The only exception is the XF, which was designed back in the days when Ford still owned Jaguar, which is based on the Ford DEW platform. But the redesigned XF is coming out very soon.



Materials and use combineed
Graphical approach

Always a trade-off...



Penalty function as an environmental tool

Environmental sustainability of refrigerators (indirect, expressed by energy costs), combined with economic sustainability

Attention to functionality [reference for data = volume]

Total cost $= Z = C_f + \alpha \cdot H_f \cdot t$

Purchase cost (C_f)

+ «life» cost

= energy consumption per unit volume

H_f (kWh/(m³· year)

Service life = t

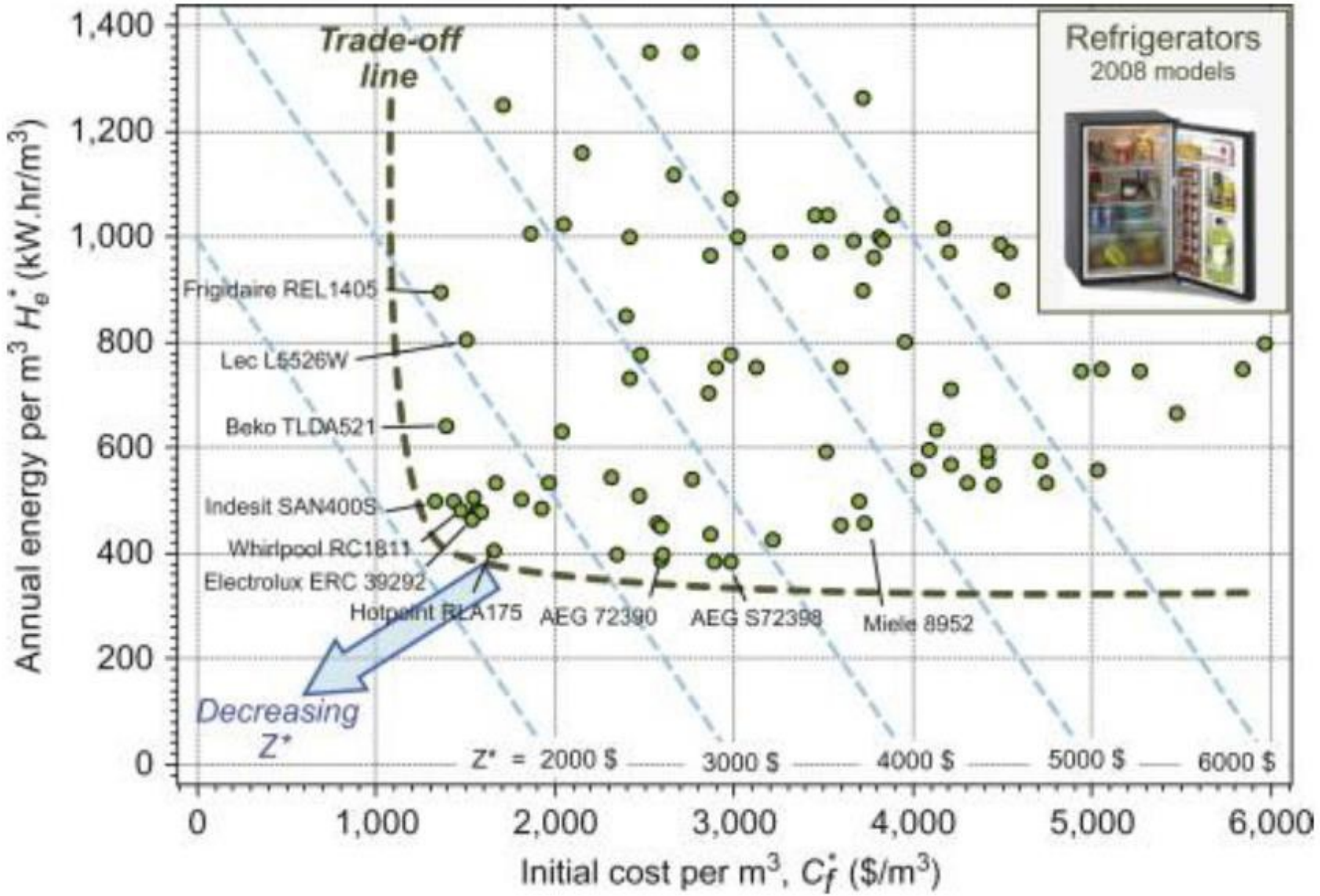
The exchange constant is the cost of energy per kWh

$$[Z] = [C_f] = \frac{\$}{m^3} \qquad [H_f] = \frac{kWh}{m^3 \cdot \text{year}} \qquad [H_f \cdot t] = \frac{kWh}{m^3}$$

$$[\alpha] = \frac{[Z]}{[H_f \cdot t]} = \frac{\frac{\$}{m^3}}{\frac{kWh}{m^3}} = \frac{\$}{kWh}$$

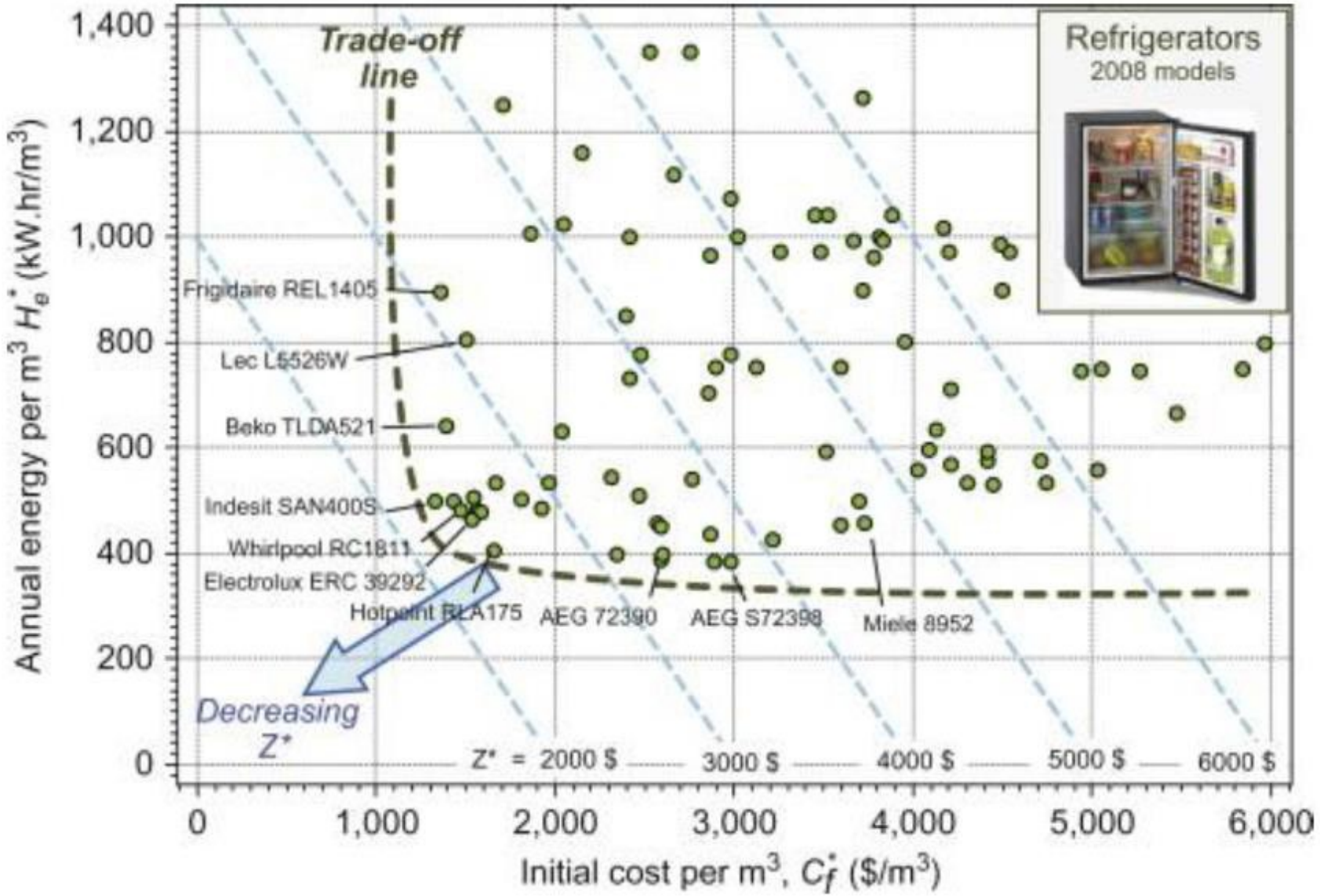
$$Z = C_f + \alpha \cdot H_f \cdot t \qquad H_f = -\frac{1}{\alpha \cdot t} \cdot C_f + \frac{Z}{\alpha \cdot t}$$

Attention: linear scale



10 years service life
Cost of energy of 0.2 $/kWh

$$H_f = -\frac{1}{2} \cdot C_f + \frac{Z}{2}$$



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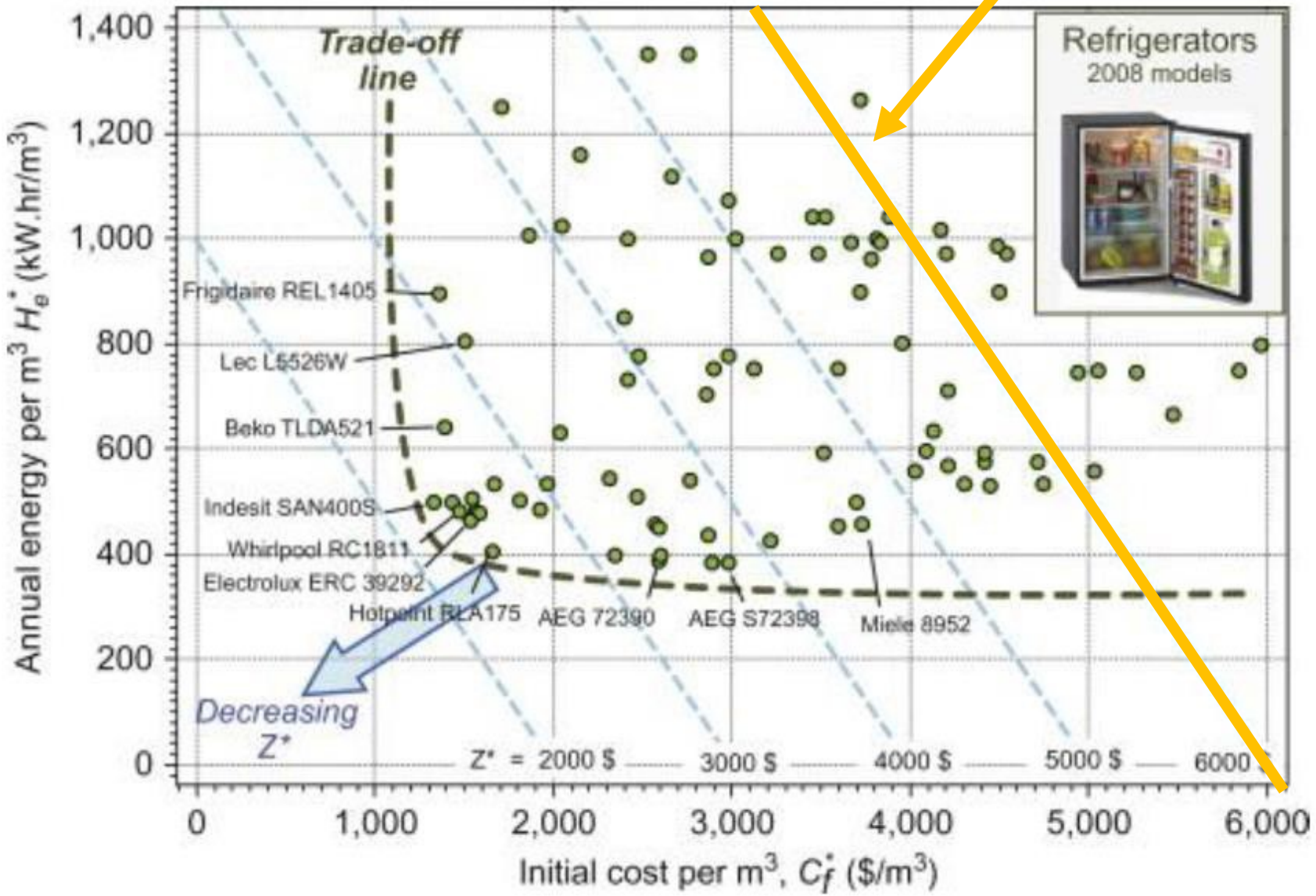

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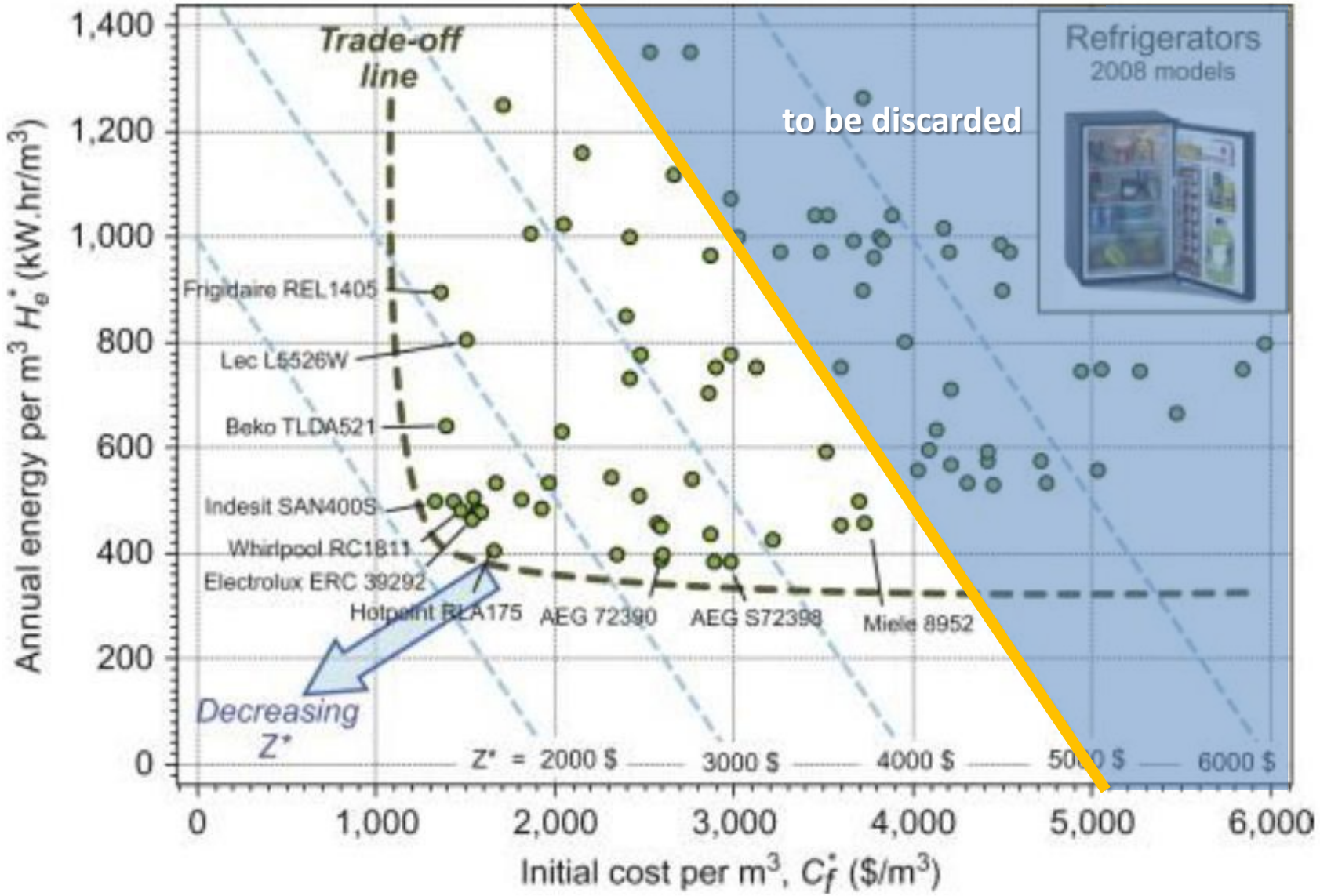

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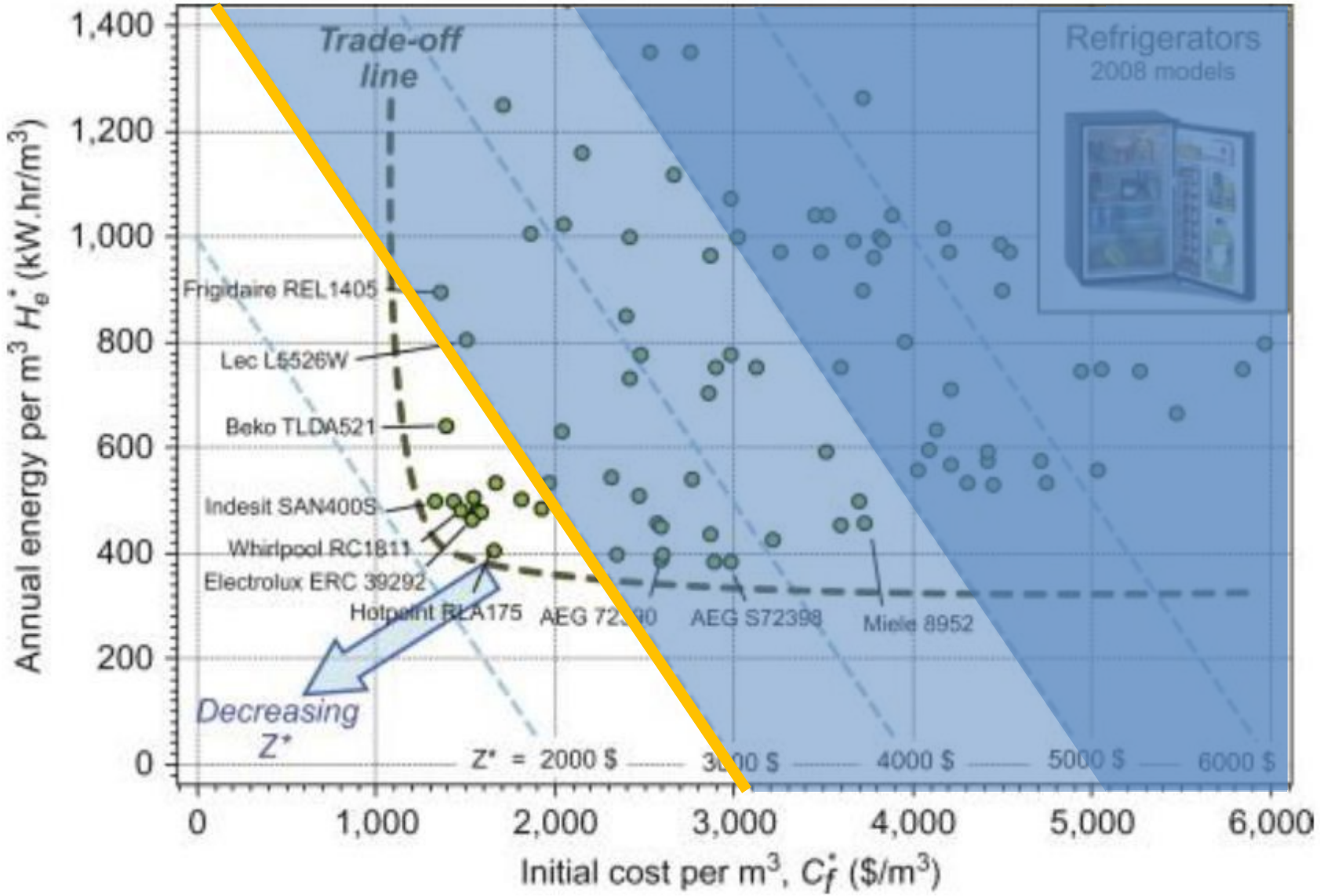

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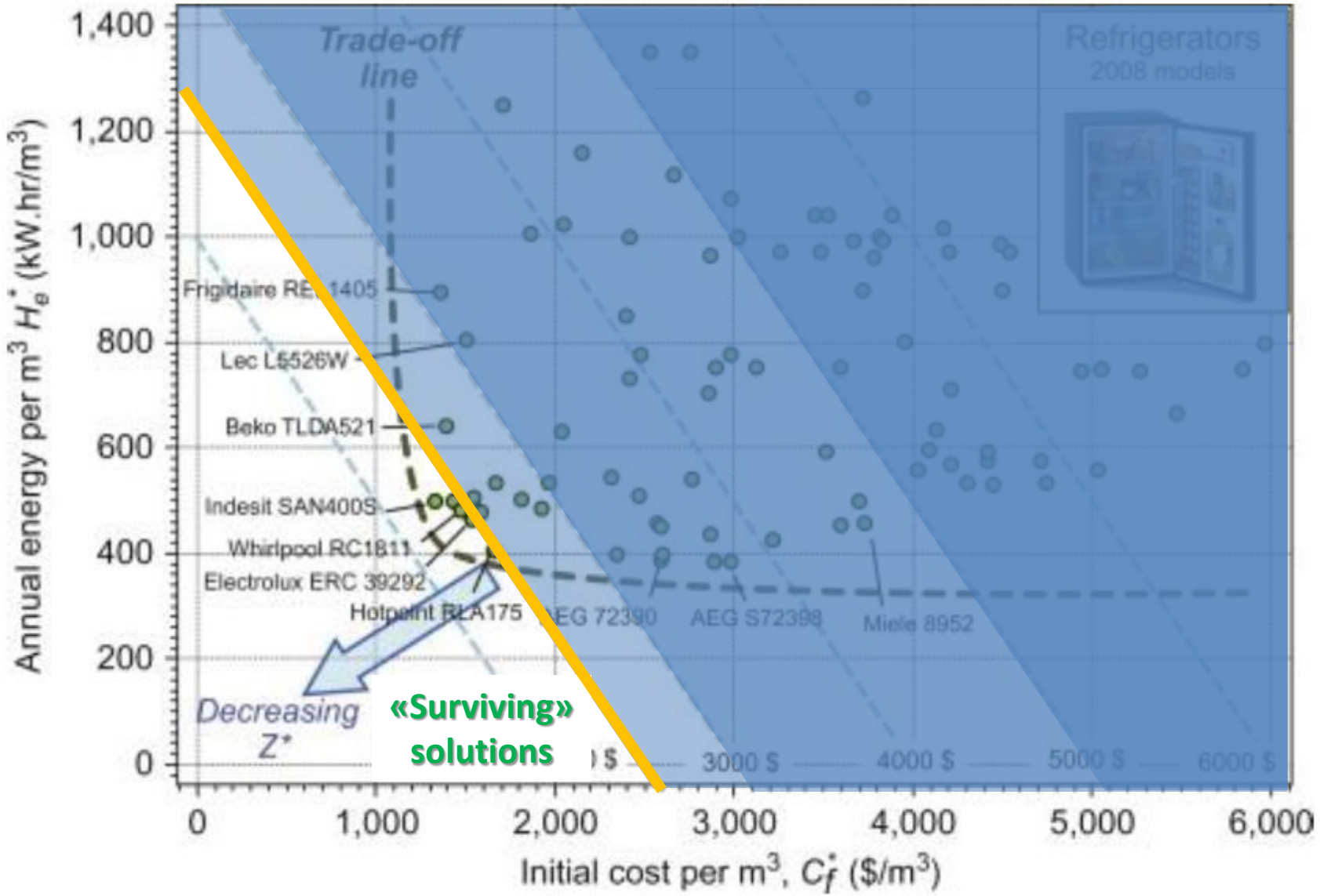
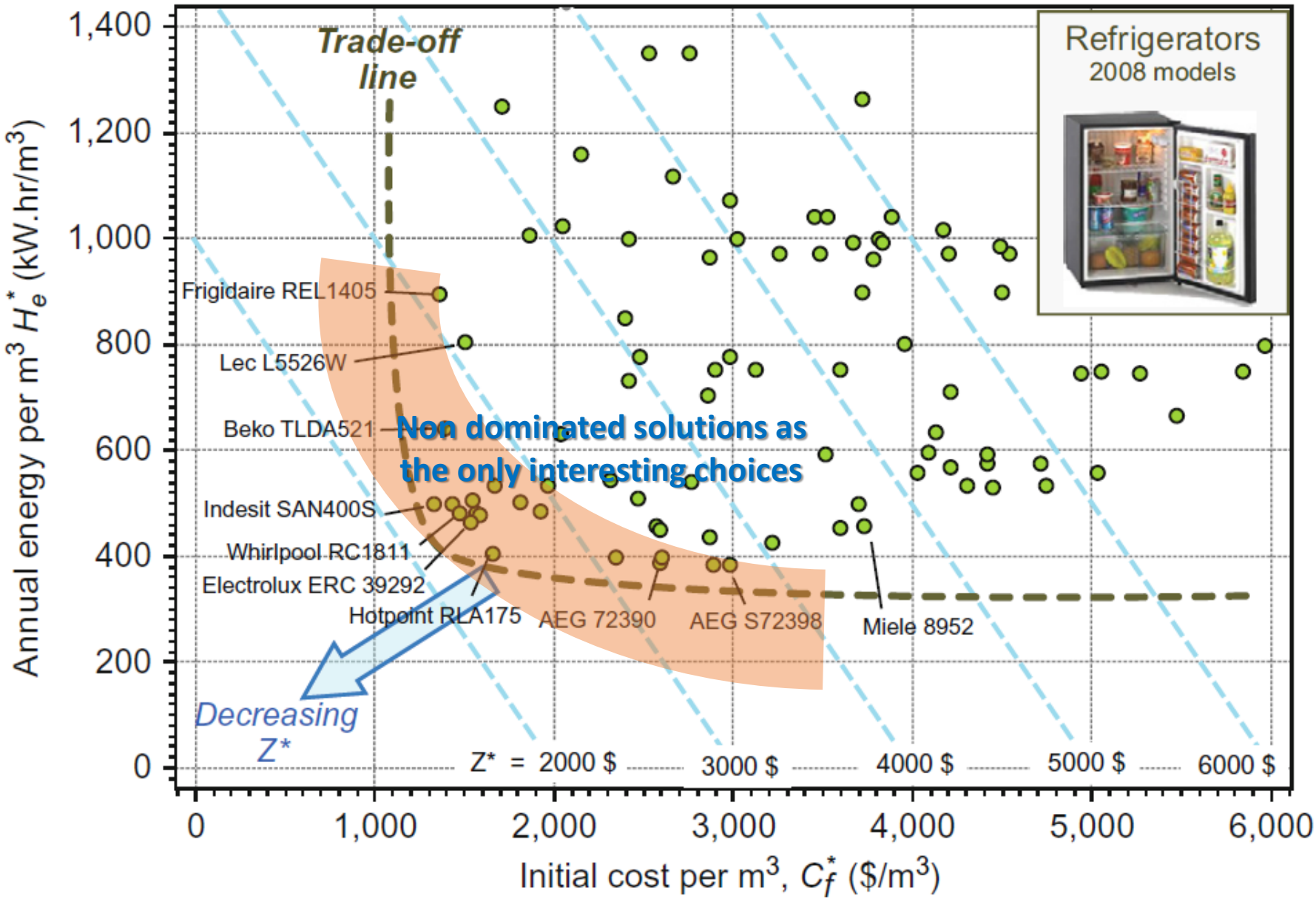
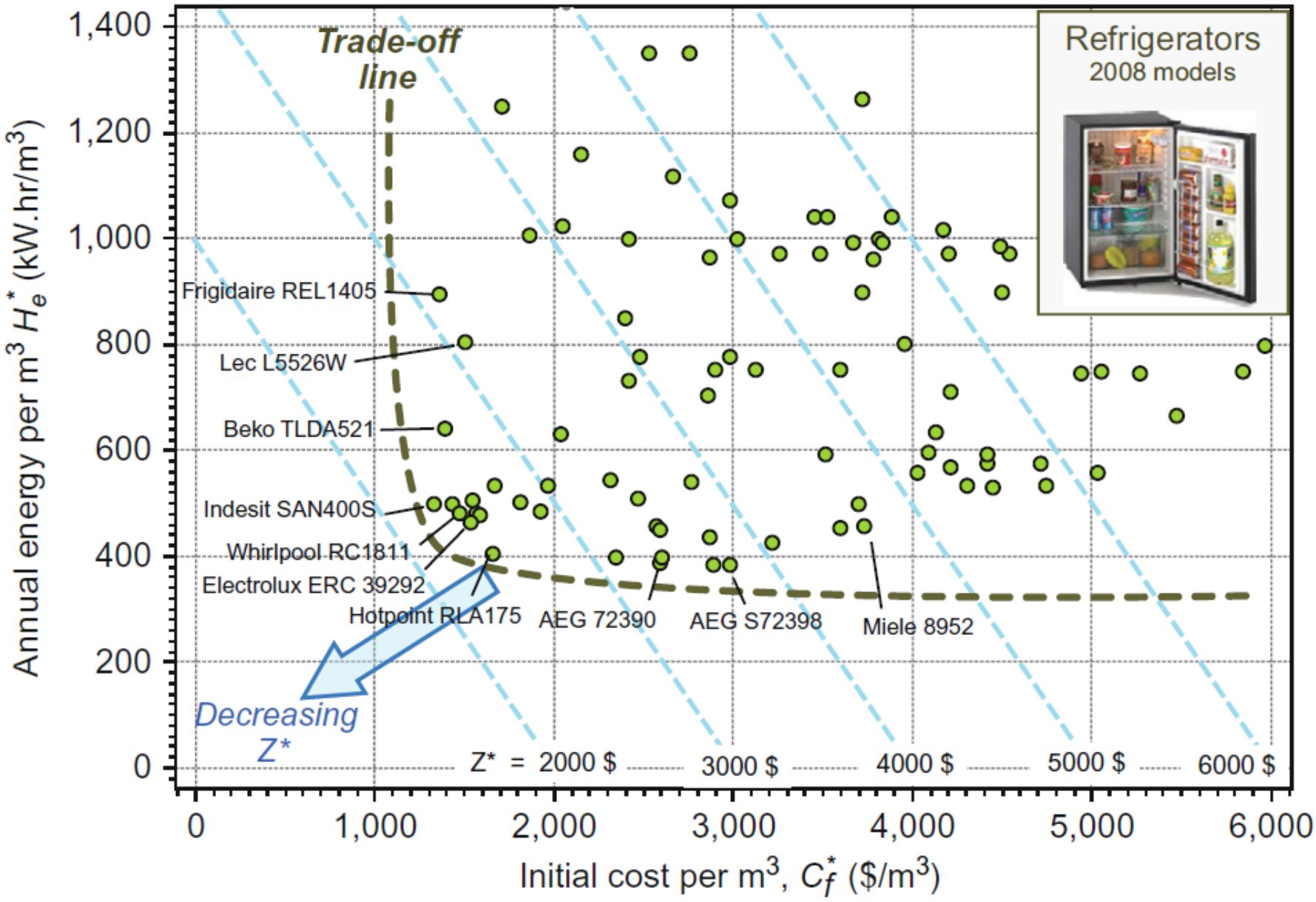



Trade-off line
Refrigerators
2008 models
Frigidaire REL1405
Lec L5526W
Beko TLDA521
Non dominated solutions as the only interesting choices
Indesit SAN400S
Whirlpool RC1811
Electrolux ERC 39292
Hotpoint RLA175
AEG 72390
AEG S72398
Miele 8952
Decreasing Z*
Z* = 2000 $
3000 $
4000 $
5000 $
6000 $
Annual energy per m3 He* (kW.hr/m3)
Initial cost per m3, Cf* ($/m3)
0
200
400
600
800
1,000
1,200
1,400
0
1,000
2,000
3,000
4,000
5,000
6,000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6000 $
Annual energy per m3 H_e^* (kW.hr/m3)
Initial cost per m3, C_f^* ($/m3)
0
200
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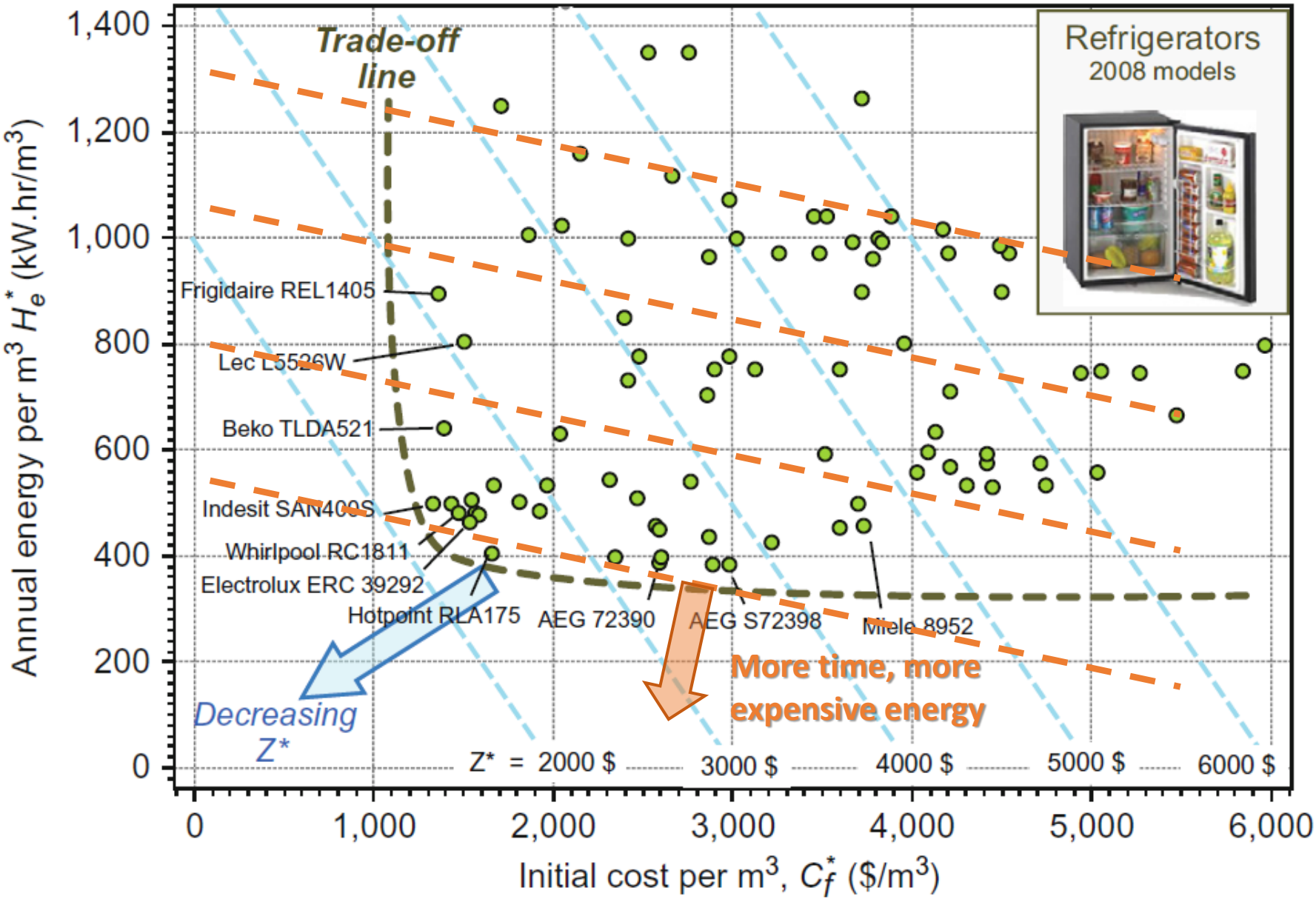
600
800
1,000
1,200
1,400
0
1,000
2,000
3,000
4,000
5,000
6,000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3000 $
4000 $
5000 $
6000 $
Annual energy per m3 H_e^* (kW.hr/m3)
Initial cost per m3, C_f^* ($/m3)
0
200
400
600
800
1,000
1,200
1,400
0
1,000
2,000
3,000
4,000
5,000
6,000

TRADE-OFF

Z = sum of characters providing some 'discomfort' to customers

$$\left[Z = C_{purchase} + \underbrace{\alpha \cdot m}_{\text{cost of component during use}} \right]$$

PENALTY FUNCTION

e.g. fuel consumption of cars

$\uparrow m \longleftrightarrow \uparrow$ fuel consumed

ECONOMIC TRADE-OFF

$$Z = C + \alpha \cdot m$$

Z reduced if $\downarrow C$

or $\downarrow m$

or $\downarrow C$ & $\downarrow m$

$$C \propto \frac{\rho C_m}{\sigma_f^{\,n}} \quad \text{or} \quad \frac{\rho C_m}{E^n}$$

solution:
select materials
with high

$$I' = \frac{\sigma_f^{\,n}}{\rho C_m} \quad \text{or} \quad I'' = \frac{E^n}{\rho C_m}$$

$$m \propto \frac{\rho}{\sigma_f^{\,n}} \quad \text{or} \quad \frac{\rho}{E^n}$$

solution:
select materials
with high

$$I' = \frac{\sigma_f^{\,n}}{\rho} \quad \text{or} \quad I'' = \frac{E^n}{\rho}$$

ECOLOGIC SUSTAINABILITY

$$Z = H + \alpha \cdot m$$

- H: energy committed for production
- α: energy committed during use
- m: TRANSPORTED COMPONENTS (DYNAMIC MODE) ↔ energy demand to move the component

$$Z' = CO_2 + \alpha' \cdot m$$

- CO_2: emission during production
- α': emission during use
- m: TRANSPORTED COMPONENTS (DYNAMIC MODE) ↔ energy demand to move the component

→ ECOLOGIC PENALTIES

ECOLOGICAL SUSTAINABILITY

USE MATERIALS WITH HIGH

$$\frac{\sigma_f^{\,n}}{\rho \cdot H_m} \quad \text{or} \quad \frac{E^n}{\rho \cdot H_m}$$

$$\frac{\sigma_f^{\,n}}{\rho\, CO_2} \quad \text{or} \quad \frac{E^n}{\rho\, CO_2}$$

τ_{CO_2} in $\frac{Kg}{Kj\ prod.}$

TO REDUCE INITIAL IMPACTS

USE MATERIALS WITH HIGH

$$\frac{\sigma_f^{\,n}}{\rho} \quad \text{or} \quad \frac{E^n}{\rho}$$

$$\frac{\sigma_f^{\,n}}{\rho} \quad \text{or} \quad \frac{E^n}{\rho}$$

TO REDUCE LIFE IMPACTS

CIRCULARITY CHALLENGE

$$I = \frac{\sigma_f^{\,n}}{\rho \cdot H_m}$$

improvable by taking H_R INSTEAD OF H_m

$$I = \frac{E^n}{\rho H_m}$$

$$H_R = (1-R)\cdot H_m + R\cdot H_{re}\left[+(1-r)\cdot H_d\right]$$

$<< H_m$ IN MANY CASES

materials with low H_m are not generally good in E and σ_f

* in case of reuse H_m replaced by $H_m^* \ll H_m$
* Reuse is efficient with limited transportation $\rightarrow$ acm

$H_m^* = 0.1 \cdot H_m + H_{transport}$ $\quad H_m^* << H_m$ with low H_{transp}

8.4 An electric kettle

Both transport and use very significant

Figure 8.3 shows a typical 2-kW electric kettle. The kettle is manufactured in Southeast Asia and transported to Europe by air freight, a distance of 12,000 km. Table 8.4 lists the materials. The kettle boils 1 liter of water in 3 minutes. It is used for this purpose, on average, twice per day for 300 days per year over a life of 3 years. At end of life the kettle is sent to the landfill. How are energy consumption and carbon emissions distributed across the phases of life?

If use phase is significant….
Actual emissions and consumption of fossil fuel depend ALSO on the energy mix of the country where the kettle is used



A 2-kW kettle

Bill of materials and processes				Material and process properties*			
Component	**Material**	**Process**	**Mass (kg)**	**Material energy (MJ/kg)**	**Process energy (MJ/kg)**	**Material CO_2 kg/kg**	**Process CO_2 kg/kg**
Kettle body	Polypropylene	Polymer molding	0.86	95	21	2.7	1.6
Heating element	Ni-Cr alloy	Wire drawing	0.026	133	22	8.3	1.7
Casing, heating element	Stainless steel	Def. processing	0.09	81	7.9	5.1	0.59
Thermostat	Nickel alloys	Wire drawing	0.02	133	22	8.3	1.7
Internal insulation	Alumina	Power forming	0.03	52	—	2.8	—
Cable sheath, 1 meter	Natural rubber	Polymer molding	0.06	66	7.6	1.6	1.3
Cable core, 1 meter	Copper	Wire drawing	0.015	71	15	5.2	1.1
Plug body	Phenolic	Polymer molding	0.037	90	13	3.0	2.2
Plug pins	Brass	Extrusion	0.03	72	3.1	6.3	0.23
Packaging, padding	Polymer foam	Polymer molding	0.015	107	11	3.7	1.6
Packaging, box	Cardboard	Construction	0.125	28	—	1.4	—
Other small components	*Proxy material:* Polycarbonate	*Proxy process:* Polymer molding	0.04	110	11	5.6	1.4
		Total mass	**1.3**				

Electric kettle



2 kW electric kettle

- Made SE Asia
- Air freight to UK
- Life: 3 years

Bill of materials and 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	Recycle
1	Heating element	Nickel-chromium alloys	Virgin (0%)	0.026	Wire drawing	Recycle
1	Casing, heating element	Stainless steel	Virgin (0%)	0.09	Rough rolling, forging	Recycle
1	Internal insulation	Alumina	Virgin (0%)	0.03	Incl. in material value	Landfill
1	Thermostat	Copper alloys	Virgin (0%)	0.02	Rough rolling, forging	Recycle
1	Plug body	Phenolics	Virgin (0%)	0.037	Polymer molding	Landfill
1	Plug pins	Brass	Virgin (0%)	0.03	Extrusion, foil rolling	Recycle
1	Cable sheath, 1 meter	Natural rubber (NR)	Virgin (0%)	0.06	Polymer molding	Landfill
1	Cable core, 1 meter	Copper	Virgin (0%)	0.015	Wire drawing	Recycle
1	Packaging, foam	Rigid Polymer Foam (MD)	Virgin (0%)	0.015	Polymer molding	Landfill
1	Packaging, cardboard	Paper and cardboard	Virgin (0%)	0.125	Incl. in material value	Recycle
1	Residual components	Polycarbonate (PC)	Virgin (0%)	0.04	Polymer molding	Downcycle

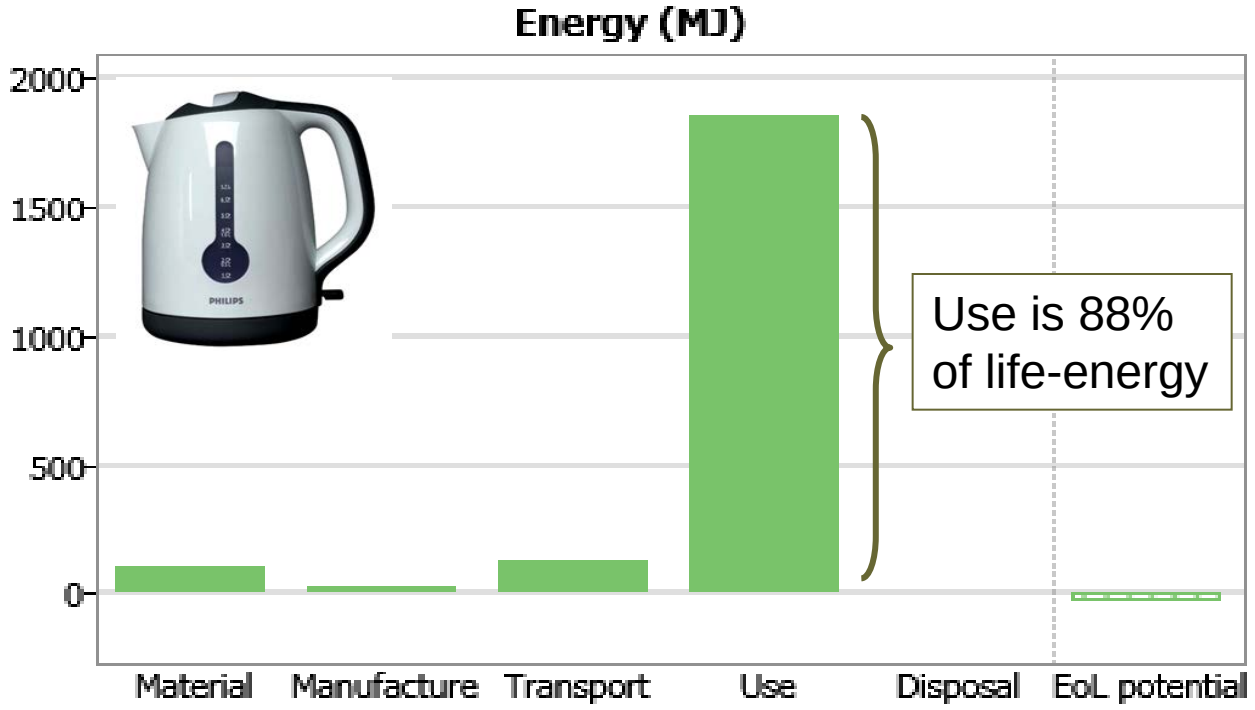
Transport

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

Use

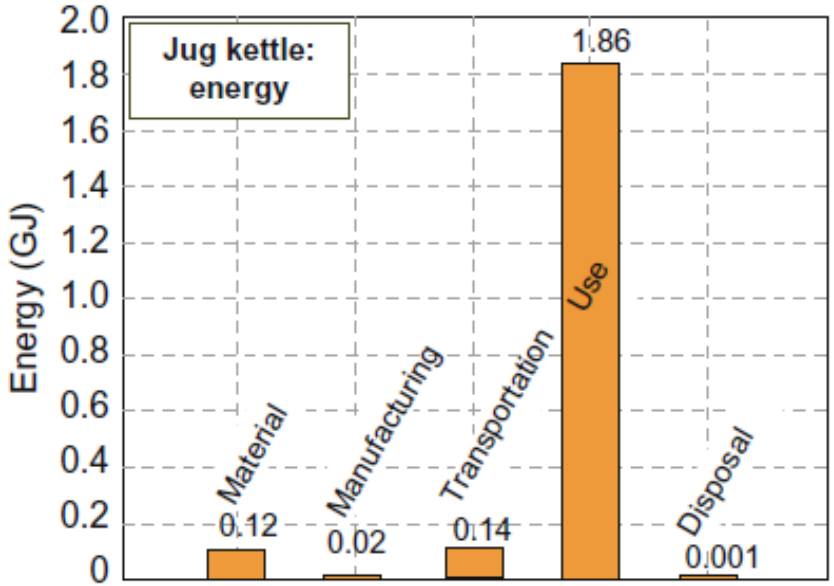
- **6 minutes per day**
- **300 days per year**
- **3 years**

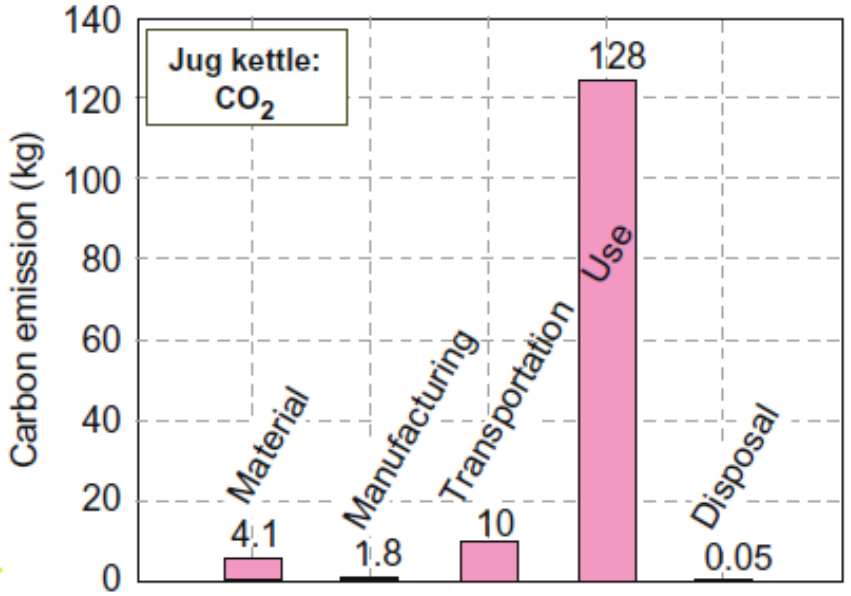
Eco audit: the jug kettle



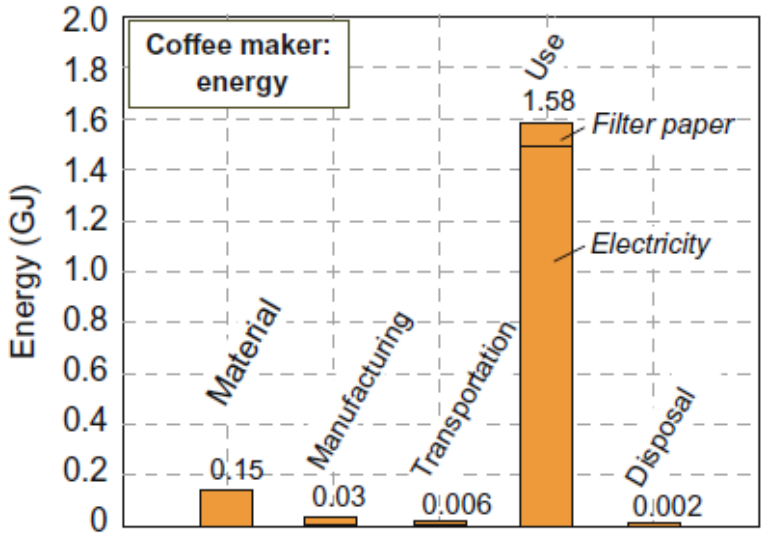
What do we learn?

- **Little gained by change of material for its own sake**
- **Much gained by insulation – double wall with foam or vacuum**
- **Or seek new concept: hot water on the fly – only as much as needed**





Home electrical devices with similar output



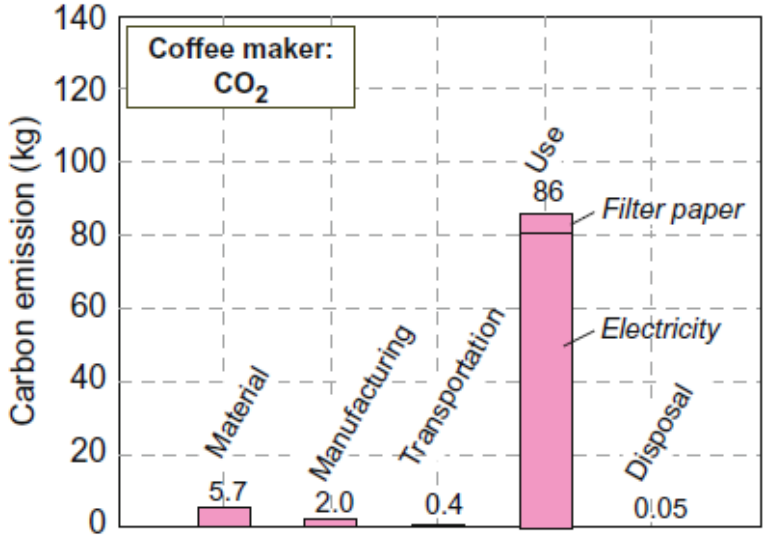


FIGURE 8.6 *The energy and carbon breakdown for the coffee maker*

8.5 A coffee maker

The 640-watt coffee maker shown in Figure 8.5 makes 4 cups of coffee in 5 minutes (requiring full power) and then keeps the coffee hot for a subsequent 30 minutes, consuming one sixth of full power. It is manufactured in Southeast Asia and shipped 17,000 km to Europe, where it is sold and used. At the end of life it is sent to the landfill.

Table 8.5 summarizes the bill of materials. The housing is injection molded polypropylene, the carafe is glass, there are a number of small steel and aluminum parts, a heating element, and, of course, a cable and plug. The control system has some simple electronics and an LED indicator. Each brew requires a filter paper that is subsequently discarded. We take the life of the coffee maker to be 5 years, over which time it is used once per day.



Bill of materials and processes				Material and process properties*			
Component	**Material**	**Process**	**Mass (kg)**	**Material energy (MJ/kg)**	**Process energy (MJ/kg)**	**Material CO_2 kg/kg**	**Process CO_2 kg/kg**
Housing	Polypropylene	Molding	0.91	95	21	2.7	1.6
Small steel parts	Steel	Rolling	0.12	32	2.7	2.5	0.2
Small aluminum parts	Aluminum	Rolling	0.08	209	5.5	12	0.4
Glass carafe	Glass (Pyrex)	Molding	0.33	25	8.2	1.4	0.7
Heating element	Ni-Cr alloy	Wire drawing	0.026	133	22	8.3	1.7
Electronics and LED	Electronics	Assembled	0.007	3000	—	130	—
Cable sheath, 1 meter	PVC	Extrusion	0.12	66	7.6	1.6	1.3
Cable core, 1 meter	Copper	Wire drawing	0.035	71	15	5.2	1.1
Plug body	Phenolic	Molding	0.037	90	13	3.0	2.2
Plug pins	Brass	Extrusion	0.03	72	3.1	6.3	0.23
Packaging, padding	Polymer foam	Molding	0.015	107	11	3.7	1.6
Packaging, box	Cardboard	Construction	0.125	28	—	1.4	—
Other components	*Proxy material:* Polycarbonate	*Proxy process:* Molding	0.04	110	11	5.6	1.4
		Total mass	**1.9**				



Bill of materials			Material properties*	
Component	**Recycle content (%)**	**Part mass (kg)**	**Embodied energy (MJ/kg)**	**CO_2 footprint (kg/kg)**
Mild steel parts	42%	23	22	1.7
Cast iron parts	69%	3.8	8.9	0.5
HSLA steel parts	Virgin (0%)	6.2	35	2.1
Stainless steel parts	38%	5.4	59	3.7
Aluminum parts	43%	1.9	134	7.6
Copper, brass parts	43%	1.8	48	3.5
Zinc parts	Virgin (0%)	0.1	72	3.8
Polystyrene parts	Virgin (0%)	2.1	92	2.9
Polyolefin parts (PP)	Virgin (0%)	1.3	94	2.7
PVC parts	Virgin (0%)	0.7	80	2.4
Nylon parts	Virgin (0%)	0.4	128	5.6
Other polymers (ABS)	Virgin (0%)	1.9	96	3.4
Rubber parts	Virgin (0%)	1.6	66	1.6
Concrete blocks[+]	Virgin (0%)	22	1.1	0.1
Cardboard packaging	Virgin (0%)	2.3	28	1.4
Wood parts	Virgin (0%)	2.5	7.4	0.4
Borosilicate glass	Virgin (0%)	0.1	25	1.4
	Total mass	**77**		

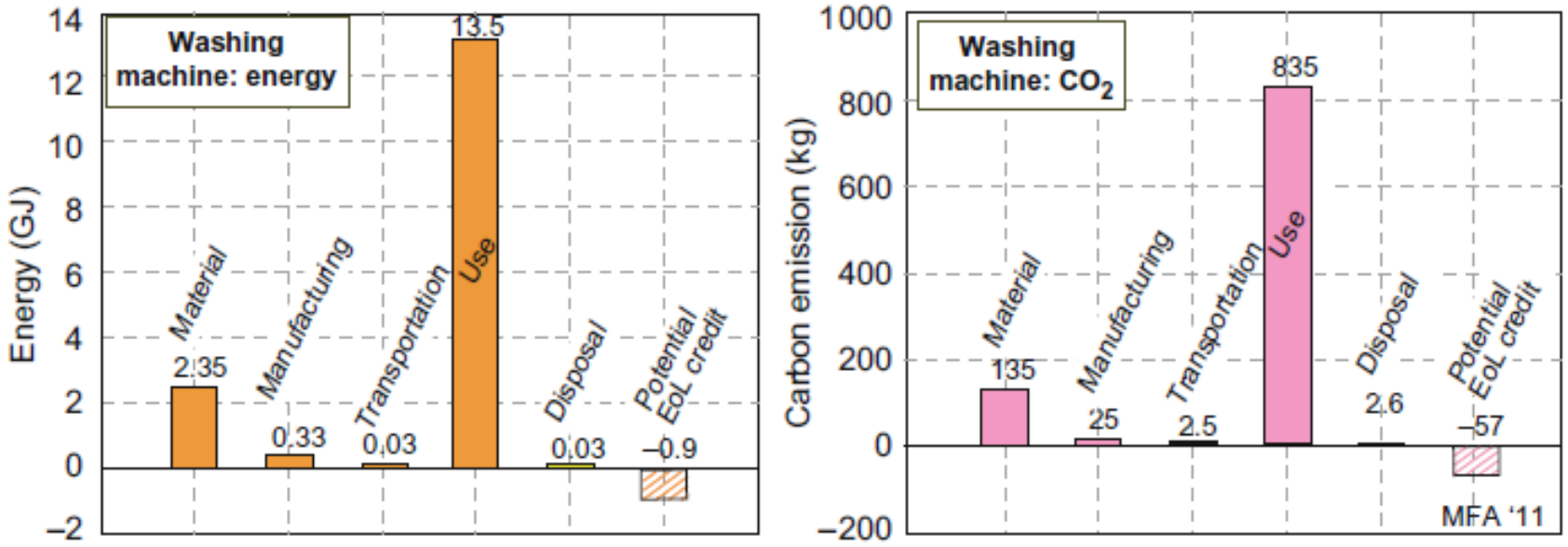
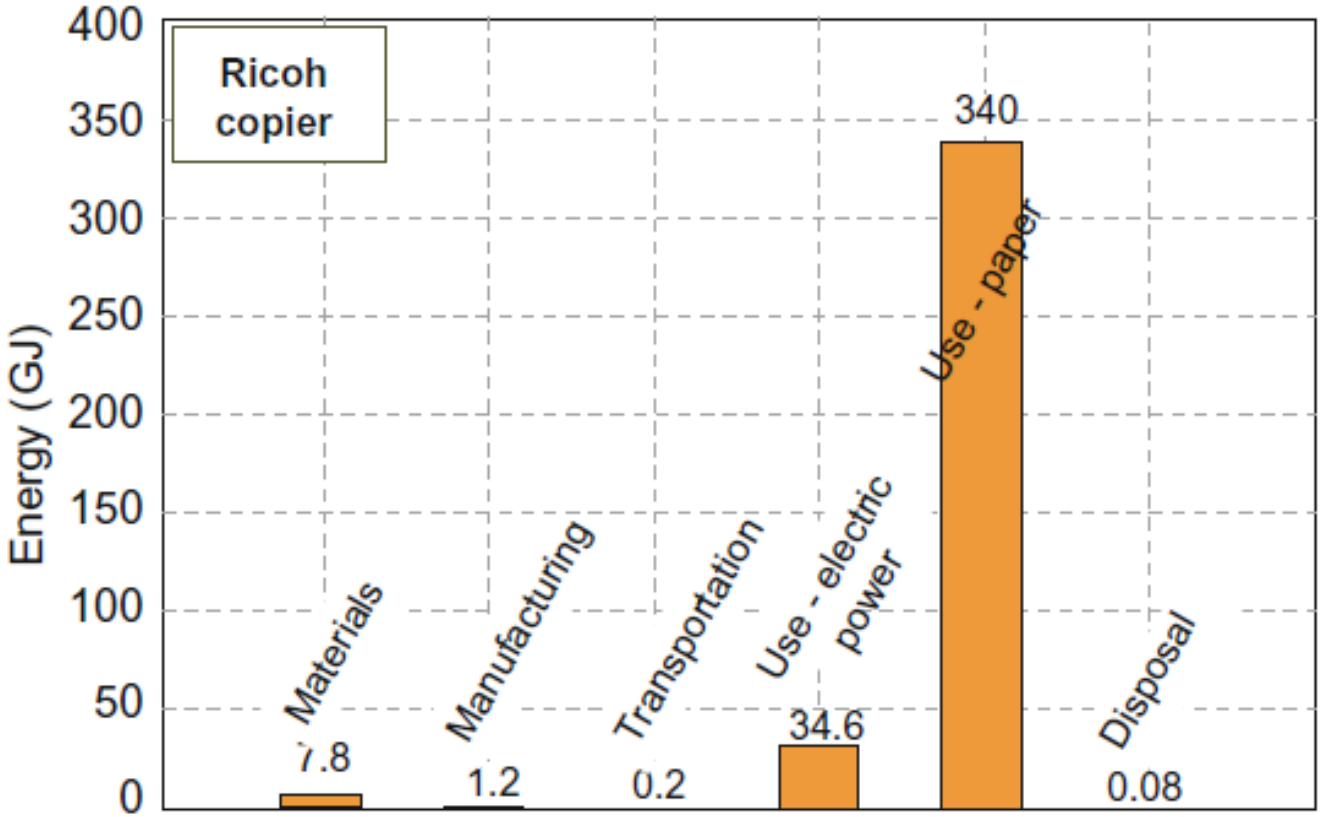


FIGURE 8.8 *The energy and carbon footprint of an A-rated washing machine, based on data from Stahel (1992) and the National Energy Foundation (2011)*

8.7 Ricoh imagio MF6550 copier

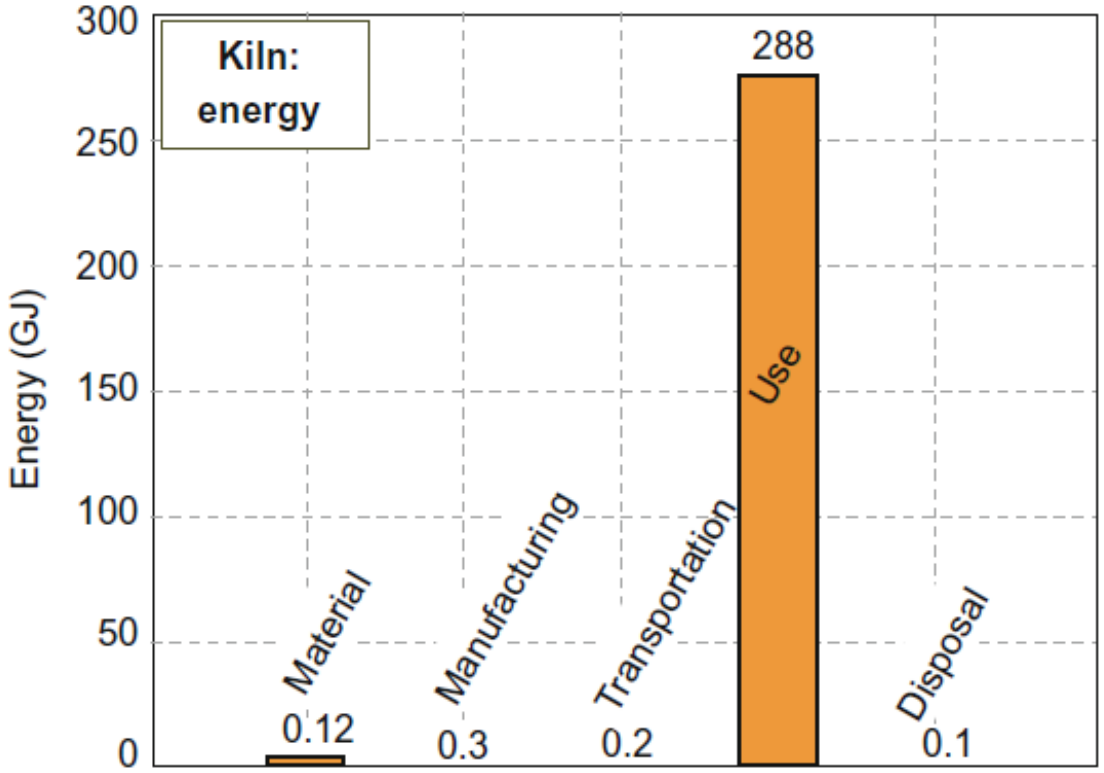
Ricoh provides Environmental Product Declarations (EPDs) for its products. The one for their MF6550 digital copier (Figure 8.9) includes an approximate bill of materials, shown on the left of Table 8.7. The typical service life of the copier is 5 years, during which time it is used 8 hours per day for 20 days per month, consuming, on average, 0.35 kW of electrical power over that time. During this time, the copier consumes 2,880,000 sheets of paper weighing 12,215 kg. At end of life, 85%



Bill of materials			Material properties*	
Component	**Recycled content* (%)**	**Part mass (kg)**	**Embodied energy (MJ/kg)**	**CO_2 footprint (kg/kg)**
Steel press parts	42%	1.1e +02	22	1.7
Zinc parts	22%	3.7	59	3.2
Copper/brass parts	43%	1.5	48	3.5
PS parts	0%	8.5	92	2.9
ABS parts	0%	4	96	3.4
PC parts	0%	2.4	110	5.6
POM parts	0%	1.4	105	4.0
PP parts	0%	1.1	95	2.7
PET parts	0%	0.8	84	2.3
Glass parts	0%	2.2	25	1.4
Neoprene parts	0%	5	101	3.7
Other materials (PC proxy)	0%	15	110	5.6
Total mass		**180**		



An electric kiln



Bill of materials			Material properties*	
Component	**Recycle content (%)**	**Part mass (kg)**	**Embodied energy (MJ/kg)**	**CO_2 footprint (kg/kg)**
Mild steel frame and casing	42%	65	22	1.7
Refractory brick	0%	500	2.8	0.2
Nichrome furnace windings	0%	5	133	8.3
Copper connectors	43%	2	48	3.5
Alumina high-temp insulation	0%	1	52	2.8
	Total mass	**572**		

Use energy outperforming materials energy

Let's change materials not for decreasing embodied energy, but for increasing heat insulation

«Simmetry» between atomic/ionic diffusion and thermal diffusion

Analogies and significant differences

For mass transfer, only D; for heat transfer, 2 coefficients are necessary

Condition	Mass transfer	Heat transfer
Stationary	$J_x = -D \cdot \frac{dC}{dx}$	$q = -\lambda \cdot \frac{dT}{dx}$
Not stationary	$\frac{\partial C}{\partial t} = D \cdot \frac{\partial^2 C}{\partial x^2}$	$\frac{\partial T}{\partial t} = a \cdot \frac{\partial^2 T}{\partial x^2}$

$$[\boldsymbol{J_x}] = [\boldsymbol{D}] \cdot \left[\frac{\boldsymbol{dC}}{\boldsymbol{dx}}\right] \rightarrow [D] = \frac{[J_x]}{\left[\frac{dC}{dx}\right]} = \frac{\frac{kg}{m^2 \cdot s}}{\frac{kg}{m^3}\Big/_{m}} = \boldsymbol{\frac{m^2}{s}}$$

$$\left[\frac{\boldsymbol{\partial C}}{\boldsymbol{\partial t}}\right] = [\boldsymbol{D}] \cdot \left[\frac{\boldsymbol{\partial^2 C}}{\boldsymbol{\partial x^2}}\right] \rightarrow [D] = \frac{\left[\frac{\partial C}{\partial t}\right]}{\left[\frac{\partial^2 C}{\partial x^2}\right]} = \frac{\frac{kg}{m^3}\Big/_{s}}{\frac{kg}{m^3}\Big/_{m^2}} = \boldsymbol{\frac{m^2}{s}}$$

«Simmetry» between atomic/ionic diffusion and thermal diffusion

Analogies and significant differences

For mass transfer, only D; for heat transfer, 2 coefficients are necessary

Condition	Mass transfer	Heat transfer
Stationary	$J_x = -D \cdot \frac{dC}{dx}$	$q = -\lambda \cdot \frac{dT}{dx}$
Not stationary	$\frac{\partial C}{\partial t} = D \cdot \frac{\partial^2 C}{\partial x^2}$	$\frac{\partial T}{\partial t} = a \cdot \frac{\partial^2 T}{\partial x^2}$

$$[q] = [\lambda] \cdot \left[\frac{dT}{dx}\right] \rightarrow [\lambda] = \frac{[q]}{\left[\frac{dT}{dx}\right]} = \frac{\frac{J}{m^2 \cdot s}}{\frac{K}{m}} = \frac{J}{m \cdot K \cdot s} = \frac{\boldsymbol{W}}{\boldsymbol{m \cdot K}}$$

$$\left[\frac{\partial T}{\partial t}\right] = [a] \cdot \left[\frac{\partial^2 T}{\partial x^2}\right] \rightarrow [a] = \frac{\left[\frac{\partial T}{\partial t}\right]}{\left[\frac{\partial^2 T}{\partial x^2}\right]} = \frac{K/_s}{K/_{m^2}} = \frac{\boldsymbol{m^2}}{\boldsymbol{s}}$$

«Simmetry» between atomic/ionic diffusion and thermal diffusion

Analogies and significant differences

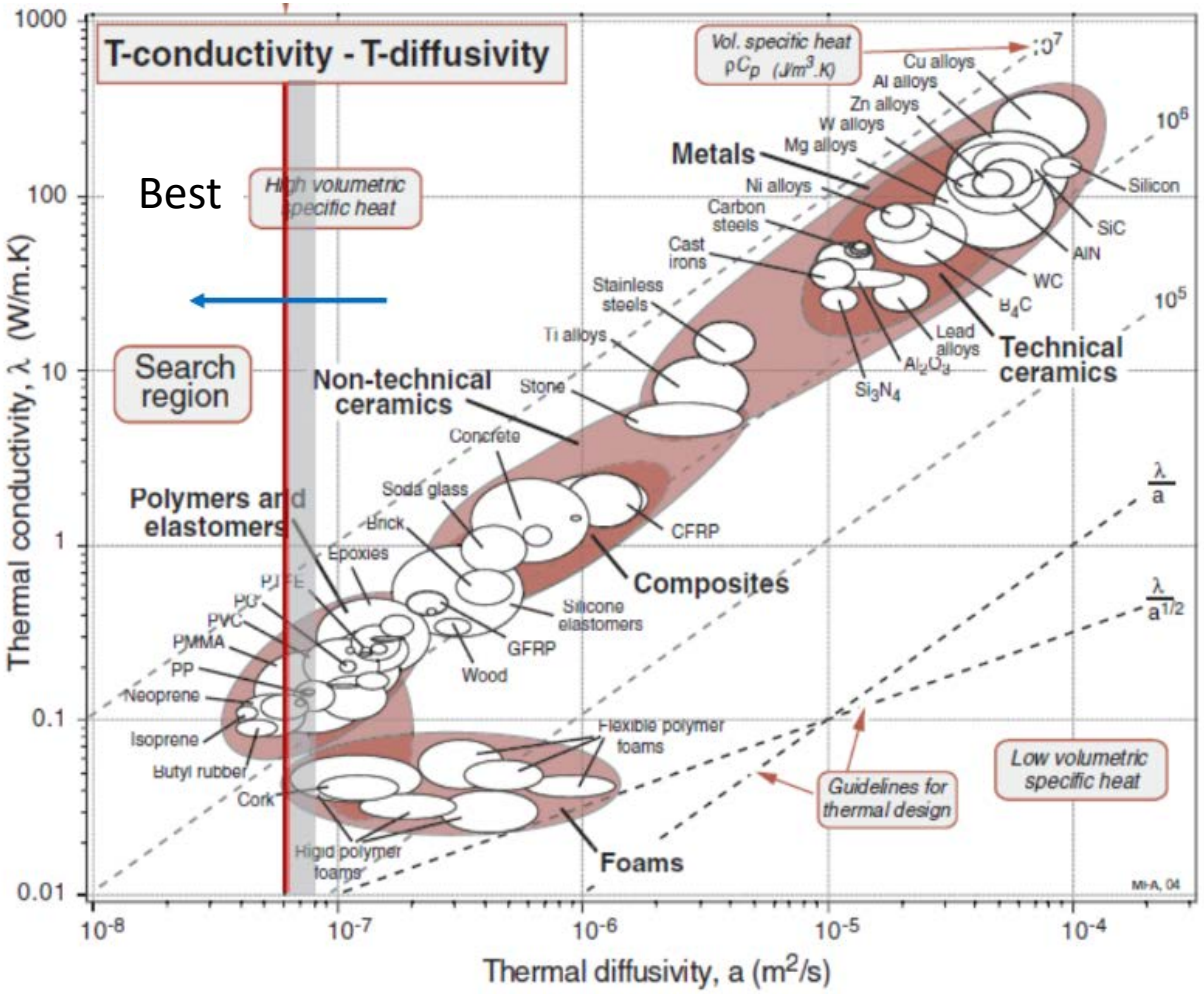
For mass transfer, only D; for heat transfer, 2 coefficients are necessary

Condition	Mass transfer	Heat transfer
Stationary	$J_x = -D \cdot \frac{dC}{dx}$	$q = -\lambda \cdot \frac{dT}{dx}$
Not stationary	$\frac{\partial C}{\partial t} = D \cdot \frac{\partial^2 C}{\partial x^2}$	$\frac{\partial T}{\partial t} = a \cdot \frac{\partial^2 T}{\partial x^2}$

$$\boldsymbol{a = \frac{\lambda}{\rho \cdot C_p}}$$

Definition of thermal diffusivity

$$[a] = \frac{[\lambda]}{[\rho] \cdot [C_p]} = \frac{\frac{J}{m \cdot K \cdot s}}{\frac{kg}{m^3} \cdot \frac{J}{kg \cdot K}} = \boldsymbol{\frac{m^2}{s}}$$



Surprise! Polymer foams, well known for the excellent thermal insulation, **do not provide the best performance**.
They possess a low thermal conductivity, but the thermal diffusivity is not the minimum one

Minimum diffusivity: **elastomers**, *like neoprene rubber (poly-chloroprene), isoprene rubber (poly-isoprene, synthetic variant of natural rubber) and butyl rubber*



Bags for cold / warm food

Neoprene rubber effectively applied



Diving suits

Neoprene foams also possible

Selection chart with limited entries



Cladding for ‘fire-free cooking kit’

http://www.bridensolutions.ca/kindle-cook-kit

Energy efficient kilns (firing of pottery ceramics)

Problem of not stationary conditions

Simplified: stationary conditions in the working time



Dispersed heat

- **Transmission towards external environment**

$$q = -\lambda \cdot \frac{dT}{dx} = \lambda \cdot \frac{T_i - T_0}{w} \left[= \frac{\{energy\}}{\{time\}\{surface\}}\right]$$

$$\boldsymbol{Q_{cond}} \left[= \frac{\{energy\}}{\{surface\}}\right] = \int_0^t q \cdot dt = q \cdot \int_0^t dt = \boldsymbol{\lambda} \cdot \frac{\boldsymbol{T_i - T_0}}{\boldsymbol{w}} \cdot \boldsymbol{t}$$

- **Heating of walls**

$$\boldsymbol{Q_{walls}} \left[= \frac{\{energy\}}{\{surface\}}\right] = \boldsymbol{C_p \cdot \rho \cdot w} \cdot \frac{\boldsymbol{T_i - T_0}}{\boldsymbol{2}}$$

Walls not completely in equilibrium with the internal temperature T_i (let's think at linear variation along thickness)

In case of «complete» heating

$$Q_{risc} \left[= \frac{\{energy\}}{\{surface\}}\right] = C_p \cdot \rho \cdot w \cdot (T_i - T_0)$$

Energy efficient kilns (firing of pottery ceramics)

Problem of not stationary conditions

Simplified: stationary conditions in the working time

Let's find the optimum wall thickness

$$Q_{disp}\left[=\frac{\{energy\}}{\{surface\}}\right]=Q_{cond}+Q_{walls}=\boldsymbol{\lambda\cdot\frac{T_i-T_0}{w}\cdot t+C_p\cdot\rho\cdot w\cdot\frac{T_i-T_0}{2}}$$

Mimimum dispersion mathematically expressed as:

$$\frac{dQ_{disp}}{dw}=-\lambda\cdot\frac{T_i-T_0}{w^2}\cdot t+C_p\cdot\rho\cdot\frac{T_i-T_0}{2}=0$$

$$-\frac{\lambda}{\tilde{w}^2}\cdot t+C_p\cdot\frac{\rho}{2}=0\rightarrow\tilde{w}=\sqrt{2\frac{\boldsymbol{\lambda}}{\boldsymbol{C_p\cdot\rho}}t}$$

$$\boldsymbol{\tilde{w}=\sqrt{2at}}$$

t = working time (holding time)

Energy efficient kilns (firing of pottery ceramics)

Problem of not stationary conditions

Simplified: stationary conditions in the working time

Let's minimize the global dissipation

$$\left(Q_{disp}\right)_{min} = Q_{disp}(\sqrt{2at}) = \lambda \cdot \frac{T_i - T_0}{\sqrt{2at}} \cdot t + C_p \cdot \rho \cdot \sqrt{2at} \cdot \frac{T_i - T_0}{2}$$

$$\left(Q_{disp}\right)_{min} = Q_{disp}\left(\sqrt{2at}\right) = (T_i - T_0) \cdot \sqrt{\frac{t}{2}} \cdot \left(\frac{\lambda}{\sqrt{a}} + C_p \cdot \rho \cdot \sqrt{a}\right)$$

Contribution of the adopted material

$$= (T_i - T_0) \cdot \sqrt{\frac{t}{2}} \cdot \left(\frac{\lambda}{\sqrt{a}} + \frac{\lambda}{a} \cdot \sqrt{a}\right)$$

$$\left(Q_{disp}\right)_{min} = Q_{disp}\left(\sqrt{2at}\right) = (T_i - T_0) \cdot \sqrt{2t} \cdot \left(\frac{\boldsymbol{\lambda}}{\sqrt{\boldsymbol{a}}}\right)$$

$$\left(\boldsymbol{Q_{disp}}\right)_{\boldsymbol{min}} = \boldsymbol{FS_{Qdisp}} \cdot \left(\frac{\boldsymbol{\lambda}}{\sqrt{\boldsymbol{a}}}\right) \quad \rightarrow \quad \boldsymbol{Q_{disp}} \geq \boldsymbol{FS_{Qdisp}} \cdot \left(\frac{\boldsymbol{\lambda}}{\sqrt{\boldsymbol{a}}}\right)$$

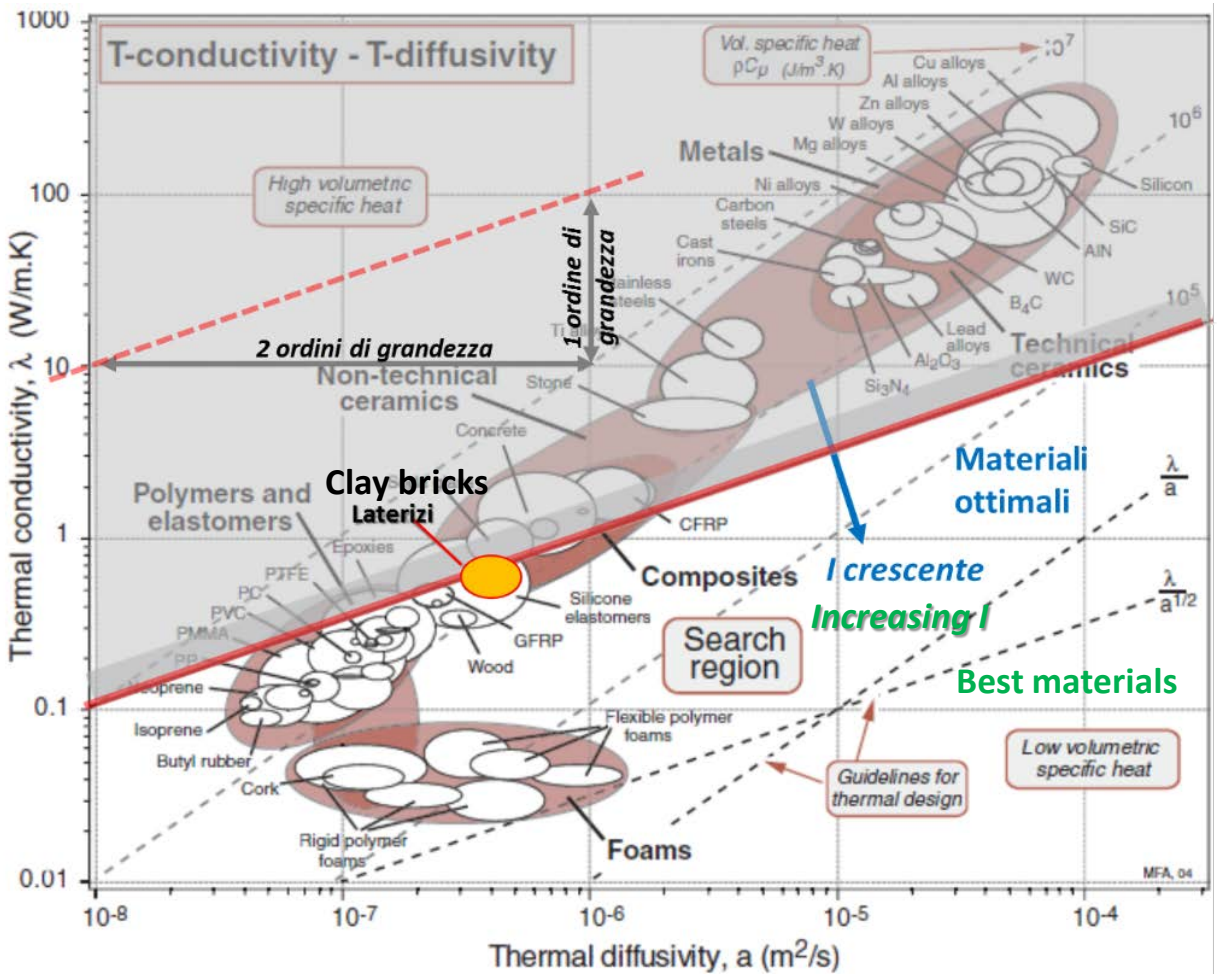
General equation

Index of thermal efficiency (to be maximized):

$$I = \frac{\sqrt{a}}{\lambda}$$

'Linearized' as follows:

$$LogI = \frac{1}{2}Loga - Log\lambda \qquad \rightarrow \qquad Log\lambda = \frac{1}{2}Loga - \mathbf{LogI}$$



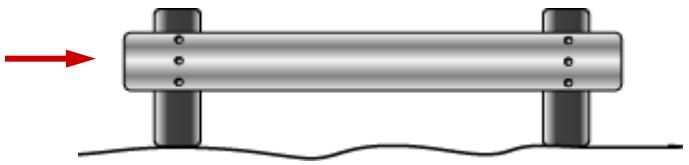
Let's skip materials with maximum service temperature below 150 °C:
Optimum = Clay bricks, with **I equal to 10^{-3} $m^2 \cdot K/(W \cdot s^{0.5})$**

$\tilde{w}$ in the order of 90-100 mm

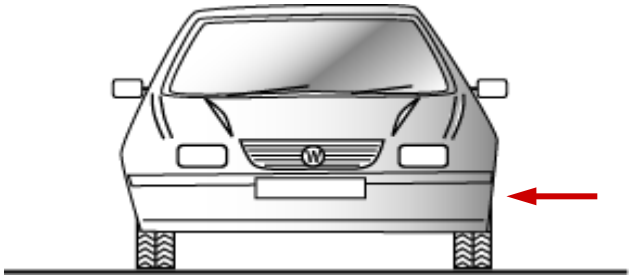
Obviously refractory bricks are better; best refractory bricks exhibit **I of approx. 3 10^{-3} $m^2 \cdot K/(W \cdot s^{0.5})$**

Materials for crash barriers

Static barrier

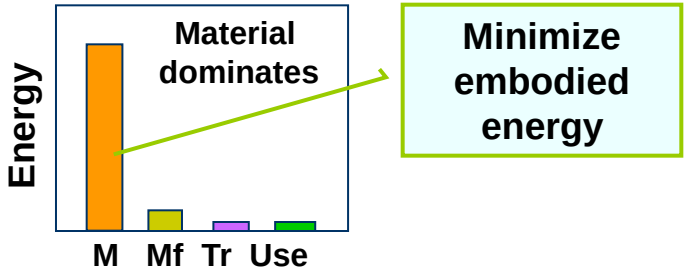


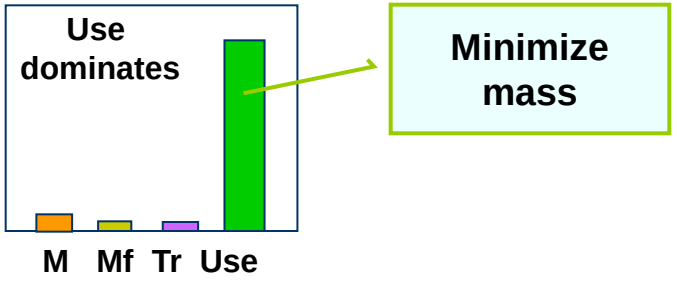
Mobile barrier



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

Dominant phase of life:





Criterion:

Bending strength per unit embodied energy

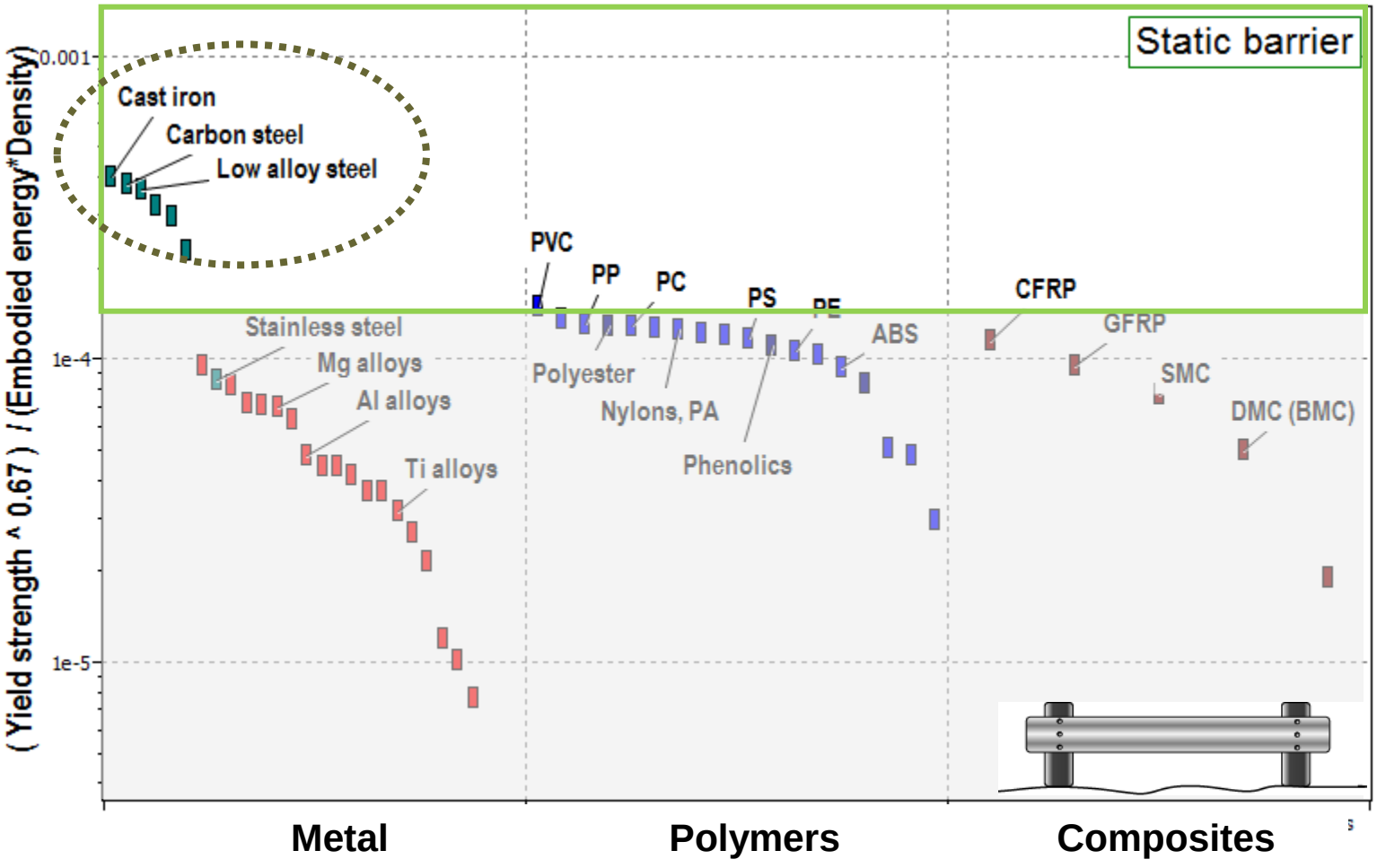
Bending strength per unit mass

Index:

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

Static barrier: the index as bar chart

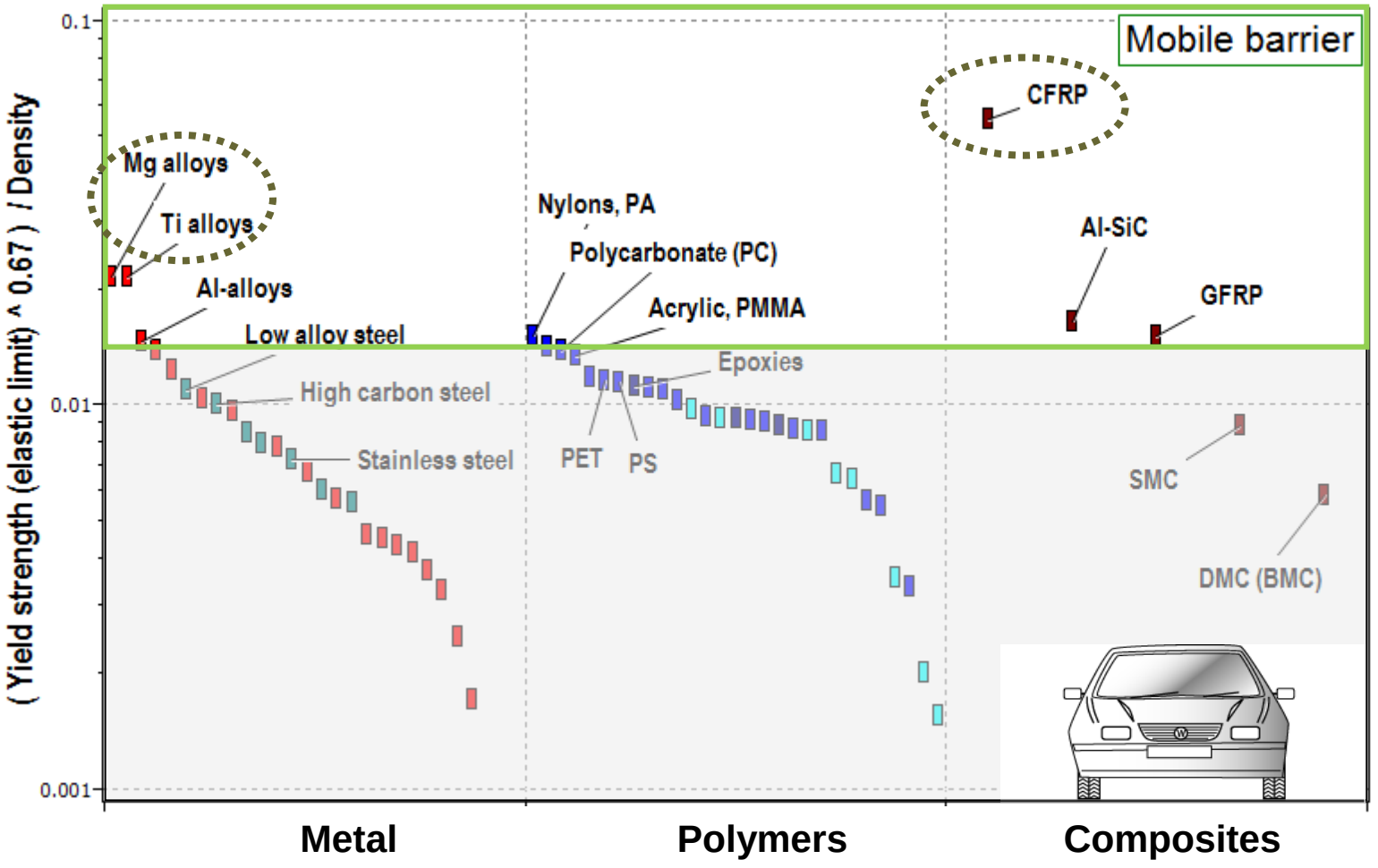
$$\frac{\sigma_y^{2/3}}{H_m \rho}$$



Selected materials: *Cast irons, steels*

Mobile barrier: the index as bar chart

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



Selected materials: *CFRP, Mg alloys, Ti alloys, Al alloys*