Sustainable Design Series of Delft University of Technology

A quick reference guide to LCA DATA and eco-based materials selection

Joost G. Vogtländer

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LCA DATA

and eco-based materials selection

Cover photo (made by Gijs Korthals Altes):
Designers can make a difference. Windmills of the 18th century in Holland are masterpieces of sustainable design. They were a source of sustainable energy, built from natural materials like wood, bricks, stone and cane. They are beautifully integrated in the Dutch landscape.

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Preface

Life Cycle Assessment (LCA) is a well-defined method to calculate the environmental burden of a product or service.
The book "A practical guide to LCA, for students designers and business managers" (Vogtländer, Fourth edition 2016) is an attempt to explain LCA in such a way that students and other interested people (non-experts) can easily and quickly understand how to do the required calculations.
Another hurdle, however, is to acquire the data required for a specific LCA calculation. Although the internet is the modern source of data, there is still a need for data guides which provide data in an easy and well accessible way. The recently developed Idemat App for IOS and Android provides fast and detailed information on regarly used materials, however, not everybody has a smartphone yet. Especially in labs and workshops, it appears that look-up tables in a reference guide are faster than a search on the internet or searches in big computer databases.
A quick reference guide like this one seems to be very useful in the early design phases, when it is essential to have a good overview of alternative design solutions.

This Quick Reference Guide on LCA data provides frequently required data in practice, and gives URLs of where more specific data can be found. The single indicators which are provided in this guide are eco-costs 2012 and the Carbon Footprint. Data are given for three end-of-life scenarios: land-fill, waste treatment as it is common in Westen Europe, and the circular economy. The underlying LCA calculations are based on LCIs from Ecoinvent v3.1 and Idemat2015.
The guide also provides charts to select the most appropriate materials for a certain function (Ashby, 2009). The educational version of the Cambridge Engineering Selector software, CES EduPack, has been used to make these material selection charts.

The data in section 2 and 3 are obsolete, since more recent data are available at https://www.ecocostsvalue.com/data-tools-books/idemat/ , respectively https://www.ecocostsvalue.com/data-tools-books/ashby-charts/ , however, data have not changed drastically, so the book can still be used for educational purposes.

My hope is that this book will not only be used by students, but also by designers, architects, and business managers (and their consultants), contributing to the wider awareness that LCA is an indispensible tool in modern design and engineering.

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The Netherlands, December 2015

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Contents

1 LCA indicator tables

On the following pages, so-called ‘single indicators’ of LCA are provided for materials and products[1]:

✓ The eco-costs (euro)

✓ The Carbon Footprint (kg CO2 equivalent)

Data in the tables are provided for 3 end-of-life scenarios, which are added to the cladle-to-gate data (note that the use phase is not included):

- Landfill (as it is common in many countries ousite Western Europe)
- Openloop recycling and combustion with heat recovery (as it is common in Western Europe)
- Closed loop recycling (“the circular economy”)

Eco-costs are ‘prevention based’ and include toxic emissions and materials depletion. A short description on the eco-costs is provided in Section A.7. A comprehensive description can be found at Wikipedia and at www.ecocostsvalue.com. The theoretical background is given in (Vogtländer et al., 2010)

Carbon Footprint is the most applied single indicator in LCA. However, data do not comprise the issue of materials depletion, which is the reason that this indicator performs less good in some specific C2C calculations (the circular economy).

The Tables are based on the LCIs of Idemat2015. Idemat2015 is based on LCIs of the Ecoinvent v3.1 database. The data on Food (Section 1.3) are based on Idemat 2010. Recent data can be found at https://www.ecocostsvalue.com/data-tools-books/idemat/

Data on materials include transport to a harbour in the North Sea region. Data on electricity, transport (rail and road) houses and food are local, as specified in the tables.

The data provided in this Guide are a selection of bigger databases. More data can be found on www.ecocostsvalue.com tab data, excel file ‘Ecocosts2012 V3.3 LCA data on products and services EI V3 Idemat2015’. This excel file comprises more than 6000 items, and includes AgriFootprnt data. Data for pure emissions can also be found on www.ecocostsvalue.com tab data, excel file ‘Ecocosts2012 V3.3 data on emissions and materials depletion’.

Chapter 2 of this guide provides charts to select the most appropriate materials for a certain function (Ashby, 2009). The Cambridge Engineering Selector software, CES EduPack was used to make these materials selection charts.

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[1] Data for the CED and ReCiPe indicators, and data for other single indicators (e.g. Ecoindicator 99, BEES, and Ecological Scarcity) can be found in the excel files at www.ecocostsvalue.com tab data.

1.1 Materials, production (cradle-to-gate) plus end-of-life

Table 1.1 Metals, production plus end-of-life scenario

metals, Idemat 2015 (per kg)	eco-costs (euro)			carbon footprint (CO2 equ.)		
end-of-life scenario	landfill	waste treatment	circular economy	landfill	waste treatment	circular economy
crude iron, virgin	0.71	0.60	0.60	1.8	1.8	1.8
carbon steel, market mix	0.79	0.68	0.68	1.9	1.9	1.9
carbon steel, secondary	0.24	0.13	0.13	0.4	0.4	0.4
carbon steel, beams	0.75	0.63	0.63	1.7	1.7	1.7
cast iron	0.34	0.23	0.23	0.7	0.7	0.7
stainless steel	0.41	0.29	0.29	1.5	1.5	1.5
stainless steel 304	3.71	3.60	0.29	5.9	5.9	1.5
stainless steel 316	4.97	4.85	0.29	7.0	7.0	1.5
aluminium, virgin	6.89	6.77	0.41	20.2	20.2	1.4
aluminium, secondary	0.52	0.41	0.41	1.4	1.4	1.4
aluminium, market mix	4.72	4.60	0.41	13.8	13.8	1.4
antimony	10.80	10.68	6.99	10.3	10.3	10.3
cadmium	3.58	3.47	0.89	4.1	4.1	4.1
chromium	16.68	16.57	6.26	26.6	26.6	26.6
cobalt	61.47	61.35	3.12	10.3	10.3	10.3
copper, virgin	6.86	6.75	0.79	4.1	4.1	1.8
copper, secondary	0.90	0.79	0.79	1.8	1.8	1.8
copper wire, plate	4.24	4.13	0.79	3.1	3.1	1.8
gallium	561.43	561.32	46.88	255.6	255.6	255.6
gold, virgin	18201	18201	193	17058	17058	1043
gold, secondary	193	193	193	1043	1043	1043
gold, market mix	8657	8657	193	8570	8570	1043
indium	488.87	488.76	64.39	219.0	219.0	219.0
lead, vigin	1.97	1.86	0.23	2.0	2.0	0.5
lead, recycled	0.34	0.23	0.23	0.5	0.5	0.5
lead, market mix	0.75	0.64	0.23	0.9	0.9	0.5
lithium	141.33	141.21	37.66	167.8	167.8	167.8
magnesium, virgin	15.12	15.00	0.37	32.9	32.9	1.9
magnesium, recycled	0.49	0.37	0.37	1.9	1.9	1.9
magnesium, market mix	8.83	8.71	0.37	19.6	19.6	1.9
manganese	1.44	1.32	1.30	3.7	3.7	3.7
mercury	928.00	927.89	920.14	12.2	12.2	12.2
molybenum	76.71	76.59	68.54	70.6	70.6	70.6
nickel, virgin	26.49	26.37	0.29	14.0	14.0	1.7

nickel, recycled	0.40	0.29	0.29	1.7	1.7	1.7
nickel, market mix	18.66	18.55	0.29	10.3	10.3	1.7
palladium, virgin	47920	47920	45	5196	5196	233
palladium, recycled	45	45	45	233	233	233
palladium, market mix	46484	46484	45	5047	5047	233
platinum, virgin	168750	168750	276	18979	18979	1223
platinum, recycled	276	276	276	1223	1223	1223
platinum, market mix	160326	160326	276	18091	18091	1223
rhodium, virgin	301972	301972	319	31656	31656	1413
rhodium, recycled	319	319	319	1413	1413	1413
rhodium, market mix	256724	256724	319	27120	27120	1413
silicon	2.26	2.15	1.92	10.5	10.5	10.5
silver, virgin	430.08	429.96	3.25	542.3	542.3	17.5
silver, recycled	3.36	3.25	3.25	17.5	17.5	17.5
silver, market mix	148.45	148.33	3.25	195.9	195.9	17.5
tantalum	179.71	179.60	86.13	304.6	304.6	304.6
tellurium	68.36	68.25	3.83	7.8	7.8	7.8
tin	24.08	23.97	11.87	21.6	21.6	21.6
titanium, virgin	28.30	28.19	2.99	90.0	90.0	16.0
titanium, recycled	3.10	2.99	2.99	16.0	16.0	16.0
titanium, market mix	22.51	22.39	2.99	73.0	73.0	16.0
tungsten	7.20	7.09	6.89	37.6	37.6	37.6
vanadium	40.75	40.64	12.02	65.8	65.8	65.8
zinc, virgin	3.22	3.10	0.17	5.2	5.2	0.8
zinc, recycled	0.28	0.17	0.17	0.8	0.8	0.8
zinc, market mix	2.54	2.43	0.17	4.2	4.2	0.8
cerium	14.16	14.05	2.73	12.3	12.3	12.3
dysprosium	1902	1902	1.31	3.9	3.9	3.9
erbium	738	737	1.31	3.9	3.9	3.9
eutropium	3626	3626	1.31	3.9	3.9	3.9
gadolinium	356	356	1.31	3.9	3.9	3.9
lanthanum	43	43	5.01	22.6	22.6	22.6
mischmetal	144	144	6.59	27.8	27.8	27.8
neodymium	272	272	8.36	37.7	37.7	37.7
praseodymium	402	402	7.85	35.4	35.4	35.4
samarium	90	90	1.31	3.9	3.9	3.9
scandium	31002	31001	1.31	3.9	3.9	3.9
terbium	2913	2912	1.31	3.9	3.9	3.9
ytterbium	895	895	1.31	3.9	3.9	3.9
yttrium	148	148	1.31	3.9	3.9	3.9
brass	3.50	3.39	0.54	3.6	3.6	1.4

For alloys, see www.ecocostsvalue.com, tab data.

Table 1.2 Polymers, production plus end-of-life scenario

polymers, Idemat 2015 (per kg)	eco-costs (euro)			carbon footprint (CO2 equ.)		
end-of-life scenario	landfill	waste treatment	circular economy	landfill	waste treatment	circular economy
Biobased polymers						
PE, biobased	0.71	0.60	0.60	1.8	1.8	1.8
PET, biobased	0.79	0.68	0.68	1.9	1.9	1.9
CA, biobased	0.24	0.13	0.13	0.4	0.4	0.4
Nylon 11, biobased	0.75	0.63	0.63	1.7	1.7	1.7
PHA/PHB, biodegradable	0.34	0.23	0.23	0.7	0.7	0.7
PLA, biodegradable	0.41	0.29	0.29	1.5	1.5	1.5
TPS, biodegradable	3.71	3.60	0.29	5.9	5.9	1.5
Elastomers						
BR/PIB	1.11	1.30	0.39	1.6	3.2	1.6
EPDM	1.55	1.72	0.63	3.1	3.1	3.1
EVA	1.02	1.18	0.58	2.1	3.6	3.0
IR	1.82	2.02	0.97	5.3	7.0	5.3
Natural rubber	0.20	-0.20	-0.20	0.2	-1.3	-1.3
NBR	1.30	1.47	0.45	1.8	1.8	1.8
Neoprene (CR)	0.87	0.90	0.30	1.7	2.5	1.7
PU, shoe soles	1.94	2.06	0.61	5.9	7.1	3.2
SAN	1.62	1.79	0.74	4.3	4.3	4.3
SBR	1.19	1.38	0.48	2.2	3.8	2.2
Silicone rubber	1.11	1.15	0.71	3.4	4.2	3.4
Thermoplasts						
ABS	1.67	1.88	0.57	4.6	6.4	3.0
ABS, 30% GF	1.23	1.38	0.62	3.4	4.7	3.4
Ionomer	1.58	1.73	0.56	4.1	5.5	2.9
Nylon 6	2.30	2.42	0.53	9.2	10.4	2.7
Nylon 6, 30% GF	1.68	1.76	0.40	6.6	7.5	2.1
Nylon 66	2.23	2.35	0.53	8.2	9.4	2.7
Nylon 66, 30% GF	1.63	1.71	0.40	5.9	6.8	2.1
PB	1.28	1.46	0.37	1.3	1.3	1.3
PC	2.30	2.49	0.53	8.1	9.7	2.8
PC, 30% GF	1.67	1.81	0.40	5.8	7.0	2.1
PE (HDPE)	1.19	1.36	0.61	2.1	3.6	3.2
PE (LDPE)	1.23	1.40	0.61	2.2	3.8	3.2
PE (LLDPE)	1.17	1.34	0.61	2.0	3.5	3.2
PE (EPE)	1.23	1.41	0.61	2.2	3.8	3.2
PEEK	4.99	5.21	1.21	22.8	24.6	6.4
PET, 30% GF	1.01	1.17	0.42	2.5	3.9	2.1
PET, amorph	1.27	1.43	0.48	3.1	4.5	2.5

PET, bottle grade	1.35	1.51	0.48	3.3	4.8	2.5
PMMA	2.04	2.16	0.50	7.4	8.6	2.6
POM	1.19	1.24	0.44	4.0	4.9	2.3
PP	1.19	1.36	0.62	2.1	3.6	3.2
PP, 30% GF	0.90	1.02	0.46	1.6	2.7	2.4
PS (EPS)	1.50	1.74	0.59	3.6	5.5	3.1
PS (GPPS)	1.52	1.76	0.59	3.7	5.6	3.1
PS (HIPS)	1.52	1.76	0.59	3.7	5.6	3.1
PTFE	1.67	1.69	0.37	5.9	6.6	1.9
PTT (Sorona)	1.12	1.03	0.36	3.3	3.5	1.9
PVAC	1.26	1.43	0.66	3.2	3.2	3.2
PVC, bulk	0.83	0.86	0.45	2.2	2.9	2.3
PVC, emulsion	0.94	0.97	0.45	2.6	3.4	2.3
PVC, suspension	0.80	0.82	0.45	2.0	2.8	2.3
PVC, market mix	0.82	0.84	0.45	2.1	2.8	2.3
PVDC	1.71	1.74	0.45	5.1	5.8	2.3
Thermosets						
Carbon fiber	1.36	1.63	1.02	4.9	7.0	4.9
Epoxy resin	2.38	2.53	1.64	6.8	8.2	6.8
MF	1.30	1.47	0.85	3.7	5.2	3.7
PF	1.32	1.49	0.66	3.1	4.6	3.1
Phenolics (Bakelite)	1.50	1.71	0.78	3.6	5.4	3.6
Polyester, unsaturated	2.01	2.18	0.48	6.0	7.5	2.5
PUR, flexfoam TDI	2.14	2.31	0.48	5.0	6.5	2.5
PUR, flexfoam MDI	2.03	2.20	0.48	4.3	5.9	2.5
PUR, rigidfoam MDI	1.94	2.11	0.48	4.4	6.0	2.5
SMC/DMC, 25% GF	0.67	0.69	0.38	1.9	2.5	1.9
SMC/DMC, 50% GF	0.59	0.61	0.33	1.6	2.0	1.6
UF	1.01	1.19	0.74	3.2	4.7	3.2

Table 1.3 Wood (kg)

wood, Idemat 2015 (per kg)	eco-costs (euro)			carbon footprint (CO2 equ.)		
end-of-life scenario	landfill	waste treatment	circular economy	landfill	waste treatment	circular economy
Class I, 50+ years (kg)						
Afrormosia, FSC, PEFC	0.12	0.01	-0.02	0.3	-0.3	-0.5
Afrormosia, natural forest	6.79	6.68	6.65	3.7	3.1	2.9
Afzelia, FSC, PEFC	0.12	0.00	-0.03	0.3	-0.4	-0.5
Afzelia, natural forest	7.29	7.18	7.15	3.7	3.1	2.9
Guaiacum wood, FSC, PEFC	0.13	0.02	-0.02	0.3	-0.3	-0.5
Guaiacum wood, natural forest	3.40	3.28	3.25	3.7	3.1	3.0
Iroko FSC, PEFC	0.14	0.03	0.00	0.3	-0.3	-0.5
Iroko, natural forest	5.09	4.98	4.95	3.8	3.2	3.0
Makore FSC, PEFC	0.12	0.00	-0.03	0.3	-0.4	-0.5
Makore, natural forest	5.13	5.02	4.99	3.7	3.1	2.9
Mansonia, FSC, PEFC	0.12	0.01	-0.02	0.3	-0.3	-0.5
Mansonia, natural forest	7.30	7.18	7.15	3.7	3.1	2.9
Moabi, FSC, PEFC	0.11	-0.01	-0.04	0.2	-0.4	-0.5
Moabi, natural forest	6.01	5.90	5.87	3.7	3.1	2.9
Padouk, African, FSC, PEFC	0.12	0.01	-0.03	0.3	-0.4	-0.5
Padouk, African, natural forest	6.79	6.67	6.64	3.7	3.1	2.9
Palissander, Indisch, FSC, PEFC	0.06	-0.06	-0.09	0.1	-0.5	-0.7
Palissander, Indisch, natural forest	4.72	4.61	4.58	3.6	3.0	2.8
Robinia	0.03	-0.09	-0.12	0.0	-0.7	-0.8
Teak, FSC, PEFC	0.19	0.08	0.05	0.4	-0.2	-0.4
Teak, natural forest	8.12	8.00	7.97	3.9	3.2	3.1
Class II, 40-50 years (kg)						
Agba/Tola, FSC, PEFC	0.15	0.03	0.00	0.3	-0.3	-0.5
Agba/Tola, natural forest	9.56	9.45	9.42	3.8	3.2	3.0
Azobe, FSC, PEFC	0.09	-0.02	-0.05	0.2	-0.4	-0.6
Azobe, natural forest	4.43	4.31	4.28	3.6	3.0	2.9
Bosse, FSC, PEFC	0.12	0.00	-0.03	0.3	-0.4	-0.5
Bosse natural forest	7.29	7.18	7.15	3.7	3.1	2.9
Bubinga, FSC, PEFC	0.11	0.00	-0.03	0.2	-0.4	-0.5
Bubinga, natural forest	5.95	5.83	5.80	3.7	3.1	2.9
Cedar, FSC, PEFC	0.15	0.04	0.01	0.3	-0.3	-0.5
Cedar, natural forest	10.84	10.72	10.69	3.8	3.2	3.0
Chestnut	0.04	-0.07	-0.10	0.0	-0.6	-0.8
Cordia/Freijo, FSC, PEFC	0.35	0.24	0.21	0.8	0.1	0.0
Cordia/Freijo, natural forest	12.50	12.39	12.35	4.2	3.6	3.4
Idigbo/Framire, FSC, PEFC	0.12	0.01	-0.02	0.3	-0.3	-0.5
Idigbo/Framire, natural forest	5.96	5.84	5.81	3.7	3.1	2.9
Mahogany, American, FSC, PEFC	0.14	0.02	-0.01	0.3	-0.3	-0.5

Mahogany, American, natural forest	7.55	7.44	7.41	3.7	3.1	3.0
Meranti, FSC, PEFC	0.24	0.12	0.09	0.5	-0.1	-0.3
Meranti, natural forest	10.10	9.99	9.96	3.9	3.3	3.2
Merbau, FSC, PEFC	0.24	0.13	0.09	0.5	-0.1	-0.3
Merbau, natural forest	5.13	5.02	4.99	4.0	3.3	3.2
Oak, European	0.02	-0.09	-0.12	-0.1	-0.7	-0.8
Purpleheart, FSC, PEFC	0.06	-0.06	-0.09	0.1	-0.5	-0.7
Purpleheart, natural forest	4.72	4.61	4.58	3.6	3.0	2.8
Red Cedar, Western	0.29	0.18	0.15	0.5	-0.1	-0.3
Utile/Sipo, FSC, PEFC	0.12	0.00	-0.03	0.3	-0.4	-0.5
Utile/Sipo, natural forest	7.41	7.30	7.27	3.7	3.1	2.9
Wenge, FSC, PEFC	0.12	0.00	-0.03	0.3	-0.4	-0.5
Wenge, natural forest	5.95	5.84	5.81	3.7	3.1	2.9
Class III, 25-40 years (kg)						
Carapa/Andiroba, FSC, PEFC	0.13	0.02	-0.02	0.3	-0.3	-0.5
Carapa/Andiroba, natural forest	6.07	5.95	5.92	3.7	3.1	3.0
Dibetou, FSC, PEFC	0.12	0.01	-0.02	0.3	-0.3	-0.5
Dibetou, natural forest	7.78	7.67	7.63	3.7	3.1	2.9
Kauri, FSC, PEFC	0.17	0.05	0.02	0.3	-0.3	-0.4
Kauri, natural forest	10.85	10.74	10.71	3.8	3.2	3.0
Kotibe, FSC, PEFC	0.10	-0.01	-0.04	0.2	-0.4	-0.6
Kotibe, natural forest	4.30	4.18	4.15	3.7	3.1	2.9
Larch, European	0.04	-0.07	-0.10	0.0	-0.6	-0.8
Mahogany, African, FSC, PEFC	0.13	0.02	-0.01	0.3	-0.3	-0.5
Mahogany, African, natural forest	8.82	8.71	8.67	3.7	3.1	3.0
Movigui, FSC, PEFC	0.09	-0.02	-0.05	0.2	-0.4	-0.6
Movigui, natural forest	4.34	4.23	4.20	3.7	3.0	2.9
Mutenye, FSC, PEFC	0.13	0.01	-0.02	0.3	-0.3	-0.5
Mutenye, natural forest	4.32	4.21	4.18	3.7	3.1	3.0
Niangon, FSC, PEFC	0.10	-0.02	-0.05	0.2	-0.4	-0.6
Niangon, natural forest	4.69	4.58	4.55	3.7	3.1	2.9
Olon, FSC, PEFC	0.13	0.01	-0.02	0.3	-0.3	-0.5
Olon, natural forest	8.98	8.87	8.84	3.7	3.1	2.9
Oregon pine/Douglas, FSC, PEFC	0.23	0.11	0.08	0.5	-0.1	-0.3
Oregon pine/Douglas, natural forest	2.83	2.72	2.69	3.9	3.3	3.1
Peroba, FSC, PEFC	0.11	0.00	-0.03	0.2	-0.4	-0.5
Peroba, natural forest	7.11	7.00	6.96	3.7	3.1	2.9
Pitch pine, FSC, PEFC	0.14	0.03	0.00	0.3	-0.3	-0.5
Pitch pine, natural forest	9.56	9.44	9.41	3.8	3.1	3.0
Sapelli, FSC, PEFC	0.11	0.00	-0.03	0.2	-0.4	-0.5
Sapelli, natural forest	6.78	6.66	6.63	3.7	3.1	2.9
Scots pine (grenen)	0.01	-0.10	-0.14	-0.1	-0.7	-0.9
Tchitola, FSC, PEFC	0.12	0.01	-0.02	0.3	-0.3	-0.5
Tchitola, natural forest	7.66	7.54	7.51	3.7	3.1	2.9
Tiama, FSC, PEFC	0.13	0.01	-0.02	0.3	-0.3	-0.5
Tiama, natural forest	8.34	8.23	8.20	3.7	3.1	3.0

Walnut	0.04	-0.08	-0.11	0.0	-0.6	-0.8
Yang/Keruing FSC, PEFC	0.17	0.05	0.02	0.4	-0.3	-0.4
Yang/Keruing, natural forest	6.90	6.79	6.76	3.8	3.2	3.0
Class IV, 12-25 years (kg)						
Aningre, FSC, PEFC	0.12	0.00	-0.03	0.3	-0.4	-0.5
Aningre, natural forest	5.74	5.63	5.60	3.7	3.1	2.9
Avodire, FSC, PEFC	0.12	0.00	-0.03	0.3	-0.4	-0.5
Avodire, natural forest	5.85	5.74	5.71	3.7	3.1	2.9
Balsa, FSC, PEFC	0.39	0.28	0.24	0.8	0.2	0.0
Balsa, natural forest	26.68	26.56	26.53	4.3	3.7	3.5
Birch	0.04	-0.07	-0.10	0.0	-0.6	-0.8
Elm	0.02	-0.09	-0.12	-0.1	-0.7	-0.8
Emeri/Quaruba, FSC, PEFC	0.09	-0.03	-0.06	0.2	-0.4	-0.6
Emeri/Quaruba, natural forest	8.45	8.34	8.31	3.6	3.0	2.9
Hemlock	0.20	0.09	0.05	0.2	-0.4	-0.5
Hickory	0.03	-0.08	-0.11	-0.1	-0.7	-0.8
Limba, FSC, PEFC	0.10	-0.01	-0.04	0.2	-0.4	-0.6
Limba, natural forest	5.28	5.16	5.13	3.7	3.1	2.9
Mengkulang, FSC, PEFC	0.20	0.08	0.05	0.4	-0.2	-0.4
Mengkulang, natural forest	8.36	8.25	8.22	3.9	3.3	3.1
Mersawa, FSC, PEFC	0.18	0.07	0.04	0.4	-0.2	-0.4
Mersawa, natural forest	7.88	7.76	7.73	3.8	3.2	3.1
Okoume FSC, PEFC	0.15	0.04	0.00	0.3	-0.3	-0.5
Okoume, natural forest	10.45	10.33	10.30	3.8	3.2	3.0
Paranapine, FSC, PEFC	0.12	0.01	-0.02	0.3	-0.4	-0.5
Paranapine, natural forest	7.30	7.18	7.15	3.7	3.1	2.9
Radiata Pine, New Zealand	0.21	0.10	0.07	0.5	-0.1	-0.3
Red oak	0.02	-0.09	-0.12	-0.1	-0.7	-0.8
Silver fir	0.03	-0.08	-0.12	0.0	-0.6	-0.8
Spruce, European	0.06	-0.06	-0.09	0.2	-0.4	-0.6
Yellow pine/Southern pine	0.02	-0.10	-0.13	-0.1	-0.7	-0.9
Class V, 6-12 years (kg)						
Abura, FSC, PEFC	0.14	0.03	0.00	0.3	-0.3	-0.5
Abura, natural forest	5.77	5.65	5.62	3.8	3.1	3.0
Ahorn	0.04	-0.07	-0.10	0.0	-0.6	-0.8
Alder	0.04	-0.07	-0.10	0.0	-0.6	-0.8
Antiaris/Koto, FSC, PEFC	0.14	0.02	-0.01	0.3	-0.3	-0.5
Antiaris/Koto, natural forest	6.85	6.74	6.71	3.7	3.1	3.0
Ash	0.03	-0.08	-0.12	0.0	-0.6	-0.8
Aspen	0.06	-0.06	-0.09	0.1	-0.6	-0.7
Beech, European	0.01	-0.10	-0.14	-0.1	-0.7	-0.8
Black poplar	0.04	-0.07	-0.10	0.0	-0.6	-0.8
Blue gum, FSC, PEFC	0.13	0.01	-0.02	0.3	-0.3	-0.5
Blue gum, natural forest	2.89	2.78	2.75	3.7	3.1	2.9
Canaria, FSC, PEFC	0.15	0.03	0.00	0.3	-0.3	-0.5
Canaria, natural forest	9.56	9.45	9.42	3.8	3.2	3.0

Cottonwood, FSC, PEFC	0.16	0.04	0.01	0.3	-0.3	-0.4
Cottonwood, natural forest	6.91	6.80	6.77	3.8	3.2	3.0
Hornbean	0.02	-0.10	-0.13	-0.1	-0.7	-0.9
Horse chestnut	0.02	-0.10	-0.13	-0.1	-0.7	-0.9
Ilomba, FSC, PEFC	0.16	0.05	0.01	0.3	-0.3	-0.4
Ilomba, natural forest	10.46	10.34	10.31	3.8	3.2	3.0
Koto, FSC, PEFC	0.13	0.01	-0.02	0.3	-0.3	-0.5
Koto, natural forest	5.96	5.85	5.82	3.7	3.1	3.0
Linden	0.02	-0.10	-0.13	-0.1	-0.7	-0.9
Platan	0.02	-0.10	-0.13	-0.1	-0.7	-0.9
Poplar	0.02	-0.10	-0.13	-0.1	-0.7	-0.9
Sycamore/Plane/Plantane	0.20	0.09	0.06	0.3	-0.3	-0.5
Wawa/Abachi, FSC, PEFC	0.18	0.06	0.03	0.4	-0.2	-0.4
Wawa/Abachi, natural forest	12.15	12.04	12.01	3.8	3.2	3.1
Willow	0.00	-0.11	-0.14	-0.1	-0.7	-0.9
Unknown durability (kg)						
Anzala/Mukulungu, FSC, PEFC	0.09	-0.03	-0.06	0.2	-0.4	-0.6
Anzala/Mukulungu, natural forest	3.41	3.30	3.27	3.6	3.0	2.9
Coromandel/Ebony, FSC, PEFC	0.16	0.05	0.02	0.3	-0.3	-0.4
Coromandel/Ebony, natural forest	5.19	5.08	5.04	3.8	3.2	3.0
Dabema, FSC, PEFC	0.11	0.00	-0.03	0.2	-0.4	-0.5
Dabema, natural forest	6.78	6.66	6.63	3.7	3.1	2.9
Emien, FSC, PEFC	0.16	0.04	0.01	0.3	-0.3	-0.4
Emien, natural forest	8.29	8.18	8.15	3.8	3.2	3.0
Incense cedar	0.30	0.19	0.16	0.5	-0.1	-0.3
Missanda/Tali, FSC, PEFC	0.09	-0.03	-0.06	0.2	-0.4	-0.6
Missanda/Tali, natural forest	3.41	3.30	3.27	3.6	3.0	2.9
Mountain ash, European	0.02	-0.10	-0.13	-0.1	-0.7	-0.9
Niove, FSC, PEFC	0.09	-0.02	-0.05	0.2	-0.4	-0.6
Niove, natural forest	5.30	5.19	5.15	3.7	3.0	2.9
Onzabili, FSC, PEFC	0.14	0.03	-0.01	0.3	-0.3	-0.5
Onzabili, natural forest	9.00	8.88	8.85	3.8	3.1	3.0
Ozigo/Igaganga, FSC, PEFC	0.11	0.00	-0.03	0.2	-0.4	-0.5
Ozigo/Igaganga, natural forest	5.46	5.34	5.31	3.7	3.1	2.9
Pear	0.02	-0.10	-0.13	-0.1	-0.7	-0.9
Pockwood, FSC, PEFC	0.13	0.02	-0.02	0.3	-0.3	-0.5
Pockwood, natural forest	3.40	3.28	3.25	3.7	3.1	3.0
Persimmon	0.03	-0.08	-0.12	-0.1	-0.7	-0.8
Zebrawood/Gonçalo-alvez, FSC, PEFC	0.10	-0.02	-0.05	0.2	-0.4	-0.6
Zebrawood/Gonçalo-alvez, natural forest	4.45	4.34	4.31	3.7	3.1	2.9
Woodproducts (kg)						
Acetylated Radiata pine (durable wood, s.g. 510 kg/m3), estimate	0.37	0.26	0.23	1.0	0.3	0.2
Acetylated Scots pine (durable wood, s.g. 590 kg/m3), estimate	0.17	0.06	0.02	0.3	-0.3	-0.4
Bamboo (local China)	0.06	-0.05	-0.08	0.2	-0.4	-0.6
CCA wood (Scots pine with chromium, copper and arsenic)	1.41	1.29	1.26	0.0	-0.6	-0.7

Cork at factory gate in Portugal	0.03	-0.08	-0.11	0.1	-0.5	-0.7
Cork granulate	0.04	-0.07	-0.10	0.2	-0.4	-0.6
Cork granulate glued = aggregate (e.g. slab for insulation)	0.28	0.16	0.13	1.1	0.5	0.4
Fibreboard hard (800 kg/m3)	0.28	0.17	0.14	1.2	0.6	0.4
MDF (750 kg/m3)	0.25	0.13	0.10	0.9	0.2	0.1
Particle board, indoor use 600 kg/m3	0.21	0.09	0.06	0.5	-0.1	-0.3
Particle board, outdoor use 600 kg/m3	0.20	0.08	0.05	0.8	0.2	0.0
Plato wood (thermal treated European Spruce, s.g. 420 kg/m3)	0.14	0.03	0.00	0.6	0.0	-0.2
Plywood Bamboo (density approx 700 kg/m3)	0.23	0.11	0.08	0.5	-0.2	-0.3
Plywood, indoor use (softwood 600 kg/m3)	0.18	0.07	0.04	0.6	0.0	-0.2
Plywood, outdoor use, Okoumei FSC, PEFC (500 kg/m3)	0.36	0.24	0.21	1.1	0.5	0.3

	The meaning of "class" according to NEN-EN 350-2		
		conditions "A"	conditions "B"
		life time	life time
I	very sustainable	>25 years	>50 years
II	sustainable	15-25 years	50-40 years
III	moderate sust.	10-15 years	25-40 years
IV	poor sustaimable	5-10 years	12-25 years
V	not sustainable	<5 years	6-12 years

conditions "A": wood in constant contact with humid soil (not underwater and not protected)

conditions "B": wood exposed to outdoor conditions (not proteted)

Table 1.4 Wood (m3)

wood, Idemat 2015 (per m3)	eco-costs (euro)			carbon footprint (CO2 equ.)		
end-of-life scenario	landfill	waste treatment	circular economy	landfill	waste treatment	circular economy
Class I, 50+ years (m3)						
Afrormosia, FSC, PEFC	87	8	-14	191	-237	-354
Afrormosia, natural forest	4753	4674	4652	2606	2178	2061
Afzelia, FSC, PEFC	96	2	-24	209	-292	-430
Afzelia, natural forest	5980	5886	5861	3038	2537	2399
Guaiacum wood, FSC, PEFC	162	20	-20	357	-407	-617
Guaiacum wood, natural forest	4244	4102	4063	4669	3905	3696
Iroko FSC, PEFC	94	20	0	205	-192	-301
Iroko, natural forest	3309	3235	3215	2447	2050	1941
Makore FSC, PEFC	77	1	-19	168	-236	-346
Makore, natural forest	3387	3312	3291	2445	2041	1931

Mansonia, FSC, PEFC	76	5	-14	166	-213	-317
Mansonia, natural forest	4525	4454	4435	2305	1926	1822
Moabi, FSC, PEFC	88	-4	-30	193	-305	-442
Moabi, natural forest	4902	4809	4783	3005	2507	2370
Padouk, African, FSC, PEFC	88	4	-19	193	-259	-383
Padouk, African, natural forest	5021	4937	4914	2746	2294	2170
Palissander, Indisch, FSC, PEFC	49	-48	-74	105	-414	-557
Palissander, Indisch, natural forest	4015	3918	3892	3038	2518	2376
Robinia	20	-64	-87	-29	-481	-605
Teak, FSC, PEFC	127	51	30	267	-139	-251
Teak, natural forest	5397	5322	5301	2561	2155	2044
Class II, 40-50 years (m3)						
Agba/Tola, FSC, PEFC	74	17	1	161	-145	-229
Agba/Tola, natural forest	4782	4725	4709	1886	1580	1496
Azobe, FSC, PEFC	96	-25	-58	209	-439	-616
Azobe, natural forest	4692	4571	4538	3866	3218	3041
Bosse, FSC, PEFC	67	2	-16	147	-205	-301
Bosse natural forest	4193	4128	4110	2130	1779	1683
Bubinga, FSC, PEFC	93	-2	-28	203	-304	-443
Bubinga, natural forest	4937	4842	4816	3066	2559	2420
Cedar, FSC, PEFC	74	18	2	159	-140	-222
Cedar, natural forest	5310	5254	5239	1850	1550	1468
Chestnut	24	-38	-54	5	-325	-415
Cordia/Freijo, FSC, PEFC	191	129	113	409	80	-11
Cordia/Freijo, natural forest	6750	6688	6671	2272	1943	1852
Idigbo/Framire, FSC, PEFC	66	4	-13	146	-190	-282
Idigbo/Framire, natural forest	3276	3213	3196	2043	1707	1615
Mahogany, American, FSC, PEFC	151	24	-10	331	-348	-534
Mahogany, American, natural forest	8382	8256	8221	4160	3482	3296
Meranti, FSC, PEFC	151	78	58	318	-73	-180
Meranti, natural forest	6465	6392	6372	2526	2135	2028
Merbau, FSC, PEFC	191	100	75	403	-86	-220
Merbau, natural forest	4108	4017	3992	3163	2674	2540
Oak, European	15	-66	-88	-40	-473	-592
Purpleheart, FSC, PEFC	50	-47	-74	106	-413	-556
Purpleheart, natural forest	4015	3919	3892	3039	2519	2377
Red Cedar, Western	108	66	54	182	-44	-106
Utile/Sipo, FSC, PEFC	74	1	-19	161	-230	-338
Utile/Sipo, natural forest	4743	4670	4650	2369	1978	1870
Wenge, FSC, PEFC	97	2	-24	212	-295	-435
Wenge, natural forest	4941	4846	4820	3075	2568	2429
Class III, 25-40 years (m3)						
Carapa/Andiroba, FSC, PEFC	79	10	-9	175	-198	-300
Carapa/Andiroba, natural forest	3700	3631	3612	2279	1906	1804
Dibetou, FSC, PEFC	68	6	-12	153	-183	-275
Dibetou, natural forest	4279	4216	4199	2050	1714	1622

Kauri, FSC, PEFC	81	25	10	165	-132	-213
Kauri, natural forest	5263	5208	5193	1838	1542	1460
Kotibe, FSC, PEFC	77	-9	-33	169	-296	-423
Kotibe, natural forest	3266	3180	3156	2791	2326	2199
Larch, European	25	-43	-62	-19	-386	-486
Mahogany, African, FSC, PEFC	85	12	-8	184	-207	-314
Mahogany, African, natural forest	5644	5571	5551	2392	2001	1894
Movigui, FSC, PEFC	67	-14	-36	148	-286	-405
Movigui, natural forest	3082	3001	2979	2597	2163	2044
Mutenye, FSC, PEFC	105	12	-14	229	-272	-410
Mutenye, natural forest	3546	3452	3427	3058	2557	2419
Niangon, FSC, PEFC	70	-11	-33	154	-279	-398
Niangon, natural forest	3333	3252	3230	2604	2170	2051
Olon, FSC, PEFC	62	6	-9	130	-167	-248
Olon, natural forest	4357	4301	4286	1803	1507	1425
Oregon pine/Douglas, FSC, PEFC	114	56	40	235	-74	-158
Oregon pine/Douglas, natural forest	1430	1372	1356	1977	1669	1584
Peroba, FSC, PEFC	86	0	-23	186	-272	-398
Peroba, natural forest	5332	5247	5223	2773	2315	2189
Pitch pine, FSC, PEFC	107	21	-2	233	-226	-351
Pitch pine, natural forest	7168	7083	7060	2820	2362	2236
Sapelli, FSC, PEFC	73	-1	-22	159	-238	-347
Sapelli, natural forest	4406	4331	4311	2401	2004	1895
Scots pine (grenen)	5	-54	-70	-51	-369	-456
Tchitola, FSC, PEFC	76	4	-16	165	-220	-325
Tchitola, natural forest	4823	4752	4732	2339	1954	1848
Tiama, FSC, PEFC	72	8	-10	157	-185	-279
Tiama, natural forest	4673	4609	4591	2089	1747	1653
Walnut	24	-52	-73	-10	-419	-532
Yang/Keruing FSC, PEFC	125	40	16	263	-195	-321
Yang/Keruing, natural forest	5177	5092	5068	2851	2392	2267
Class IV, 12-25 years (m3)						
Aningre, FSC, PEFC	67	1	-17	147	-208	-305
Aningre, natural forest	3330	3264	3246	2148	1793	1696
Avodire, FSC, PEFC	65	2	-15	142	-194	-287
Avodire, natural forest	3219	3157	3139	2039	1703	1611
Balsa, FSC, PEFC	59	41	37	123	31	6
Balsa, natural forest	4001	3984	3980	640	549	524
Birch	29	-46	-67	7	-397	-507
Elm	14	-60	-81	-36	-433	-542
Emeri/Quaruba, FSC, PEFC	46	-13	-29	95	-219	-306
Emeri/Quaruba, natural forest	4354	4295	4279	1872	1557	1471
Hemlock	98	42	27	117	-182	-264
Hickory	24	-67	-92	-44	-533	-667
Limba, FSC, PEFC	57	-6	-24	124	-218	-312
Limba, natural forest	2956	2892	2875	2056	1714	1620

Mengkulang, FSC, PEFC	141	60	38	297	-137	-256
Mengkulang, natural forest	5938	5858	5835	2746	2312	2193
Mersawa, FSC, PEFC	116	43	23	244	-147	-254
Mersawa, natural forest	5041	4968	4948	2452	2061	1954
Okoume FSC, PEFC	66	16	2	141	-128	-202
Okoume, natural forest	4596	4546	4532	1659	1390	1316
Paranapine, FSC, PEFC	65	4	-13	141	-189	-280
Paranapine, natural forest	3940	3879	3862	2004	1674	1583
Radiata Pine, New Zealand	96	44	30	238	-37	-113
Red oak	15	-65	-87	-39	-467	-584
Silver fir	13	-38	-52	-14	-289	-364
Spruce, European	26	-27	-41	79	-202	-280
Yellow pine/Southern pine	10	-52	-69	-47	-377	-467
Class V, 6-12 years (m3)						
Abura, FSC, PEFC	79	15	-3	171	-171	-265
Abura, natural forest	3229	3165	3148	2103	1761	1667
Ahorn	28	-45	-65	6	-385	-492
Alder	24	-37	-53	5	-319	-407
Antiaris/Koto, FSC, PEFC	60	10	-4	132	-140	-215
Antiaris/Koto, natural forest	3049	2998	2984	1667	1395	1321
Ash	21	-59	-81	-22	-450	-567
Aspen	26	-24	-38	22	-246	-320
Beech, European	7	-74	-96	-46	-480	-599
Black poplar	20	-31	-44	4	-264	-338
Blue gum, FSC, PEFC	114	12	-16	235	-314	-465
Blue gum, natural forest	2603	2501	2473	3340	2791	2640
Canaria, FSC, PEFC	123	28	2	267	-240	-380
Canaria, natural forest	7938	7843	7817	3130	2623	2484
Cottonwood, FSC, PEFC	69	19	5	153	-116	-190
Cottonwood, natural forest	3042	2991	2978	1671	1402	1328
Hornbean	12	-74	-97	-54	-512	-638
Horse chestnut	7	-44	-58	-33	-307	-383
Ilomba, FSC, PEFC	77	22	7	167	-126	-207
Ilomba, natural forest	5019	4964	4949	1823	1530	1449
Koto, FSC, PEFC	71	7	-10	158	-184	-278
Koto, natural forest	3339	3275	3258	2090	1748	1654
Linden	8	-53	-70	-39	-369	-459
Platan	10	-61	-80	-45	-424	-528
Poplar	7	-43	-57	-32	-301	-374
Sycamore/Plane/Plantane	124	54	34	187	-189	-292
Wawa/Abachi, FSC, PEFC	69	25	12	150	-88	-154
Wawa/Abachi, natural forest	4739	4695	4683	1495	1257	1192
Willow	0	-51	-65	-51	-326	-401
Unknown durability (m3)						
Anzala/Mukulungu, FSC, PEFC	81	-26	-56	177	-398	-555
Anzala/Mukulungu, natural forest	3207	3100	3070	3420	2845	2688

Coromandel/Ebony, FSC, PEFC	181	55	21	380	-292	-476
Coromandel/Ebony, natural forest	5709	5584	5549	4175	3503	3319
Dabema, FSC, PEFC	77	-1	-23	169	-253	-369
Dabema, natural forest	4677	4598	4576	2549	2128	2012
Emien, FSC, PEFC	56	15	4	122	-98	-158
Emien, natural forest	2985	2944	2933	1364	1144	1084
Incense cedar	116	72	60	195	-40	-105
Missanda/Tali, FSC, PEFC	79	-24	-52	172	-378	-528
Missanda/Tali, natural forest	3072	2969	2941	3277	2727	2577
Mountain ash, European	11	-69	-91	-51	-478	-596
Niove, FSC, PEFC	80	-17	-44	173	-346	-489
Niove, natural forest	4505	4408	4381	3106	2586	2444
Onzabili, FSC, PEFC	77	14	-3	168	-168	-260
Onzabili, natural forest	4948	4885	4868	2065	1729	1637
Ozigo/Igaganga, FSC, PEFC	73	-2	-22	160	-238	-347
Ozigo/Igaganga, natural forest	3547	3473	3453	2402	2005	1896
Pear	11	-67	-88	-49	-465	-579
Pockwood, FSC, PEFC	162	20	-20	357	-407	-617
Pockwood, natural forest	4244	4102	4063	4669	3905	3696
Persimmon	24	-71	-97	-48	-559	-698
Zebrawood/Gonçalo-alvez, FSC, PEFC	88	-15	-43	193	-357	-508
Zebrawood/Gonçalo-alvez, natural forest	4008	3905	3877	3298	2748	2597
Woodproducts (m3)						
Acetylated Radiata pine (durable wood, s.g. 510 kg/m3), estimate	190	132	116	490	177.1	91.2
Acetylated Scots pine (durable wood, s.g. 590 kg/m3), estimate	100	33	15	198	-162.8	-261.7
Bamboo (local China)	44	-36	-57	136	-291.3	-408.6
CCA wood (Scots pine with chromium, copper and arsenic)	648	595	581	17	-263.7	-340.9
Cork at factory gate in Portugal	5	-12	-17	14	-77.7	-102.9
Cork granulate	6	-11	-15	31	-60.6	-85.8
Cork granulate glued = aggregate (e.g. slab for insulation)	42	25	20	170	78.0	52.8
Fibreboard hard (800 kg/m3)	242	145	119	1017	497.6	355.1
MDF (750 kg/m3)	185	100	76	640	181.7	56.0
Particle board, indoor use 600 kg/m3	140	62	41	352	-63.7	-177.7
Particle board, outdoor use 600 kg/m3	131	56	35	506	102.9	-7.7
Plato wood (thermal treated European Spruce, s.g. 420 kg/m3)	64	13	-1	279	3.8	-71.6
Plywood Bamboo (density approx 700 kg/m3)	160	80	59	323	-105.1	-222.4
Plywood, indoor use (softwood 600 kg/m3)	109	40	22	365	-1.6	-102.2
Plywood, outdoor use, Okoumei FSC, PEFC (500 kg/m3)	179	122	107	558	252.4	168.6

Table 1.5 Textile materials, production plus end-of-life scenario

Textile materials, Idemat 2015 (per kg)	eco-costs (euro)			carbon footprint (CO2 equ.)		
end-of-life scenario	landfill	waste treatment	circular economy	landfill	waste treatment	circular economy
acrylic	1.33	1.50	0.63	3.1	3.1	3.1
bio-cotton India	1.88	1.77	1.72	2.2	1.6	1.4
bio-cotton USA	1.47	1.36	1.31	2.2	1.6	1.4
cotton, China	2.15	2.04	1.99	3.7	3.2	2.9
cotton, USA	1.74	1.63	1.57	3.1	2.5	2.2
cotton, market mix	2.00	1.89	1.84	3.2	2.7	2.4
elastane (PU)	1.91	2.00	0.48	5.1	6.4	2.5
fleece, from PET	1.76	1.89	0.48	8.7	10.1	2.5
jute, India irrigation	0.75	0.64	0.59	0.9	0.3	0.0
jute, India rain fed	0.22	0.12	0.06	0.6	0.0	-0.3
jute, market mix	0.38	0.27	0.21	0.7	0.1	-0.2
kenaf, India	0.64	0.53	0.48	0.8	0.2	-0.1
kenaf, market mix	0.55	0.44	0.39	0.8	0.2	-0.1
nylon (PA)	2.15	2.38	0.53	8.7	9.9	2.7
PET ("polyester")	1.30	1.43	0.48	3.1	4.5	2.5
PLA, biobased	1.14	0.33	0.46	3.5	2.8	2.4
Sorona, biobased	1.00	1.03	0.36	3.3	3.5	1.9
viscose (rayon), biobased	0.44	0.34	0.28	1.7	1.1	0.8
wool, USA (per 100 gram)	0.06	0.60	0.60	1.9	1.9	1.8

Table 1.6 Building materials, production plus end-of-life scenario

Building materials , Idemat 2015 (per kg)	eco-costs (euro)			carbon footprint (CO2 equ.)		
end-of-life scenario	landfill	waste treatment	circular economy	landfill	waste treatment	circular economy
Cement (Corus)	0.18	0.04	0.04	0.2	0.2	0.2
Cement (Portland)	0.29	0.15	0.15	0.9	0.9	0.9
Gypsum, from exhaust gas desulferization	0.15	0.00	0.00	0.0	0.0	0.0
Bitumen	0.95	1.10	0.86	0.5	2.0	0.7
Red clay brick, for housing and roads, packed	0.19	0.05	0.05	0.3	0.3	0.3
Refractory brick, fireclay, packed	0.35	0.21	0.21	1.0	1.0	1.0
Roof tiles	0.20	0.05	0.05	0.4	0.4	0.4
Sand-lime brick	0.18	0.04	0.04	0.2	0.2	0.2
Concrete	0.17	0.02	0.02	0.1	0.1	0.1
Concrete (reinforced, 40 kg steel for 1000 kg)	0.19	0.05	0.05	0.2	0.2	0.2

Crushed concrete aggregate (per 100 kg)	0.41	0.27	0.27	0.8	0.8	0.8
Cork slab insulation	0.50	0.35	0.21	1.6	1.6	1.6
Glass wool	0.62	0.47	0.47	1.4	1.4	1.4
Rockwool	0.47	0.33	0.33	1.2	1.2	1.2
Clinker	0.20	0.05	0.05	0.3	0.3	0.3
Linoleum	1.79	1.64	1.64	3.1	3.1	3.1
Slags (Corus)	0.14	0.00	0.00	0.0	0.0	0.0
Gravel (per 100 kg)	0.57	0.57	0.57	1.4	1.4	1.4
Sand (per 100 kg)	0.19	0.19	0.19	0.4	0.4	0.4
PE (EPE, epanded polyethylene)	1.26	1.41	0.23	2.2	3.8	1.1
PS (EPS, expandable polystyrene)	1.53	1.74	0.25	3.6	5.5	1.3
PVAC (wood glue, polyvinyl acetate)	1.29	1.43	1.19	3.2	4.8	3.5
PVC (Polyvinylchloride), market mix	0.85	0.84	0.22	2.1	2.8	1.1
PUR flex. block foam TDI	2.19	2.28	0.41	5.1	6.4	2.1
Geotextiles (PP, 500 dTex, woven)	1.66	1.80	0.68	4.5	6.0	3.6

Table 1.7 Other materials, production plus end-of-life scenario

Other materials , Idemat 2015 (per kg)	eco-costs (euro)			carbon footprint (CO2 equ.)		
end-of-life scenario	landfill	waste treatment	circular economy	landfill	waste treatment	circular economy
Glass, uncoated for windows etc.	0.35	0.24	0.07	1.0	1.0	1.0
Borosilicate, estimate	0.45	0.34	0.26	1.8	1.8	1.4
Ceramic glass, estimate	0.58	0.46	0.46	2.5	2.5	2.5
Recycled borosilicate glass, estimate	0.38	0.26	0.26	1.4	1.4	1.4
Recycled silica glass, estimate	0.47	0.36	0.36	1.9	1.9	1.9
Silica glass, estimate	0.58	0.46	0.36	2.5	2.5	1.9
Glass bottles	0.40	0.28	0.07	1.1	1.1	1.1
Glass from recycled bottles, estimate	0.18	0.07	0.07	0.4	0.4	0.4
Glare 1-3/2-0.3	6.53	6.41	6.41	16.7	16.7	16.7
Glare 3-3/2-0.2	4.81	4.69	4.69	12.3	12.3	12.3
Glare 3-6/5-0.4	4.84	4.72	4.72	11.9	11.9	11.9
Glare 4-6/5-0.4	16.76	16.65	16.65	42.2	42.2	42.2
Hylite (1 m2, 1.2 mm thickness, 1.8 ton/m3)	5.19	5.07	5.07	12.7	12.7	12.7
Alumina, estimate	3.11	2.99	2.99	7.3	7.3	7.3
Aluminium nitride, estimate	3.84	3.73	3.73	9.1	9.1	9.1
Boron carbide, estimate	1.71	1.60	1.60	8.6	8.6	8.6
Glaze (in addition to porcelain and stoneware)	1.88	1.77	1.77	0.0	0.0	0.0
Porcelain	0.20	0.08	0.08	0.4	0.4	0.4
Silicon carbide, estimate	1.46	1.35	1.35	6.6	6.6	6.6
Silicon, estimate	1.01	0.89	0.89	3.9	3.9	3.9
Silicon nitride, estimate	1.12	1.00	1.00	4.8	4.8	4.8
Stoneware	0.18	0.07	0.07	0.4	0.4	0.4

Tungsten carbide, estimate	1.04	0.93	0.93	4.6	4.6	4.6
Zirconia, estimate	21.94	21.83	21.83	4.8	4.8	4.8
Board and brown paper ("kraft")	0.26	0.15	0.13	1.0	0.4	0.7
Board and recycled paper ("test liner")	0.13	0.02	0.02	0.7	0.1	0.1
Paper, woodfree uncoated (virgin paper)	0.34	0.23	0.13	1.2	0.6	0.7

For chemicals, agricultural products, fibres, special fuels (which are not in Table 1.18), and many other products, see www.ecocostsvalue.com tab data.

Table 1.8 Electronics

Electronics , Idemat 2015 (per kg)	eco-costs (euro)			carbon footprint (CO2 equ.)		
end-of-life scenario	landfill	waste treatment	circular economy	landfill	waste treatment	circular economy
AA battery, alkaline (per piece)	0.04	0.03	0.02	0.1	0.1	0.1
AA battery, Li-ion (per piece)	0.18	0.17	0.11	0.2	0.2	0.2
electric cord, 6A, 1320W (per m)	0.31	0.12	0.07	0.2	0.2	0.2
electric motor <500W (per kg)	3.62	3.50	2.00	4.2	4.2	4.2
IC logic type (per kg)	355.50	355.38	214.24	775.8	775.8	775.8
IC memory type (per kg)	154.35	154.24	137.65	599.8	599.8	599.8
LCD, screen 17 inch (per piece)	113.25	113.13	86.69	343.0	343.0	343.0
lead battery, cars (per kg)	0.81	0.69	0.35	0.9	0.9	0.9
LED (per kg)	79.14	79.03	73.84	317.2	317.2	317.2
Li-ion batt, laptop (per kg)	5.59	5.47	2.76	7.9	7.9	7.9
Li-ion batt, cars (per kg)	8.84	8.73	2.59	11.7	11.7	11.7
LCD (per kg)	20.30	20.19	15.49	62.0	62.0	62.0
mica (per kg)	0.41	0.30	0.29	1.6	1.6	1.6
AA battery, NiCd (per piece)	0.16	0.15	0.12	0.2	0.2	0.2
C battery, NiCd (per piece)	0.30	0.28	0.21	0.4	0.4	0.4
NiMH batt, laptop (per kg)	62.78	62.67	17.69	22.3	22.3	22.3
NiMH batt, scooter (per kg)	82.26	82.14	19.07	19.9	19.9	19.9
PCB, no components (per kg)	38.04	37.92	32.96	132.3	132.3	132.3
PCB, desktop (per kg)	72.42	72.30	47.63	171.6	171.6	171.6
PCB, laptop (per kg)	102.09	101.98	72.74	274.7	274.7	274.7
solder, lead (per kg)	14.84	14.73	7.27	13.3	13.3	13.3
solder, leadfree (per kg)	32.21	32.09	14.35	26.9	26.9	26.9
solder, electronics (per kg)	15.64	15.52	7.84	14.1	14.1	14.1
wafer (per m2)	0.84	0.84	0.81	3.5	3.5	3.5

1.2 Processing, gate-to-gate

Table 1.9 Metal processing, basic data, gate-to-gate

Metal processing , Idemat 2015	eco-costs (euro)	carbon footprint (CO2 equ.)
deep drawing steel (kg)	0.095	0.40
rolling steel (kg)	0.113	0.27
drilling steel (kg removed)	0.013	0.07
milling steel (kg removed)	0.013	0.07
turning steel (kg removed)	0.013	0.07
electroplating chrome (m3)	1.92	2.87
electroplating nickel (m3)	1.31	1.92
electroplating zinc outside use, per 10 years (m3)	4.87	3.04
electroplating zinc, inside use or painted (m3)	0.45	1.52
hot-dip coating zinc, inside use or painted (m3)	1.84	3.35
phosphating (Fe s) (m3)	0.14	0.69
phosphating (Zn i) (m3)	0.03	0.02
phosphating (Zn s) (m3)	0.02	0.01
powder coating Al (m3)	1.37	3.46
powder coating steel (m3)	1.09	3.99
welding, electric, MIG (m)	0.27	1.23
welding, shipbuilding (m)	34.49	156.47
welding steel, arc (m)	0.10	0.16
welding steel, gas (m)	0.10	0.18

Table 1.10 Polymer processing, basic data, gate-to-gate

Polymer processing , Idemat 2015 (per kg)	eco-costs (euro)	carbon footprint (CO2 equ.)
blow moulding, bottles	0.33	1.4
blow moulding, PVC film	0.13	0.5
extrusion	0.13	0.4
extrusion, PVC	0.11	0.4
injection moulding	0.33	1.4
injection moulding, PVC	0.17	0.3
thermoforming	0.18	0.5

For more processing data of specific materials see www.ecocostsvalue.com tab data (Autoclave molding energy, Casting energy, Coarse machining energy, Compression molding energy, Extrusion, foil rolling energy, Filament winding energy, Fine machining energy, Glass molding energy, Grinding energy, Metal powder forming energy, Non-conventional machining energy, Polymer extrusion energy, Polymer extrusion energy, Resin spray up energy, Resin transfer molding (RTM) energy, Rough rolling, forging energy, Vaporization energy, Wire drawing energy).

Table 1.11 Wood processing,basic data, gate-to-gate

Wood processing , Idemat 2015	eco-costs (euro)	carbon footprint (CO2 equ.)
acrylic varnish, transp. (kg)	0.73	1.2
acrylic varnish, white (kg)	2.22	2.2
alkyd paint, transp, solvent (kg)	1.33	2.3
alkyd paint, transp, water (kg)	0.77	1.4
alkyd paint, white, solvent (kg)	3.53	3.7
alkyd paint, white, water (kg)	3.14	3.0
alkyd paint, emissions (kg)	1.24	1.2
power sawing (hr)	2.08	1.2
shaving, hardwood (kg removed)	0.01	0.0
shaving, softwood (kg removed)	0.02	0.0

Table 1.12 Textile processing, basic data, gate-to-gate

Textile processing , Idemat 2015 (per kg)	eco-costs (euro)	carbon footprint (CO2 equ.)
dyeing, India	0.52	2.2
dyeing, Europe	0.42	2.2
heat setting	0.17	0.9
knitting 83 dtex	0.05	0.3
knitting 200 dtex	0.02	0.1
knitting 300 dtex	0.01	0.1
pretreatment of cotton	0.23	1.3
spinning cotton 45 dtex	2.10	11.3
spinning cotton 70 dtex	1.35	7.2
spinning cotton 100 dtex	0.95	5.1
spinning cotton 150 dtex	0.63	3.4
spinning cotton 200 dtex	0.47	2.5
spinning cotton 300 dtex	0.32	1.7
spinning cotton 400 dtex	0.24	1.3
spinning cotton 500 dtex	0.19	1.0
spinning polymers	0.17	0.9
spinning viscose	0.04	0.2
texturing polymer fibres	0.09	0.5
weaving 15 dtex	9.24	49.6
weaving 30 dtex	4.62	24.8
weaving 45 dtex	3.08	16.5
weaving 70 dtex	1.98	10.6
weaving 100 dtex	1.39	7.4
weaving 150 dtex	0.92	5.0
weaving 200 dtex	0.69	3.7
weaving 300 dtex	0.46	2.5

1.3 Food

Table 1.13 Food, data from Denmark

food (per kg) Idemat 2010 (danish food database)	eco-costs (euro)	carbon footprint (kg CO_2 eq)
at farm gate (per kg)		
Cattle, from farm	2.66	10.75
Chicken, from farm	0.55	1.67
Egg	0.65	1.78
Milk, conventional, from farm	-0.01	-0.10
Pork, from farm	0.68	2.12
Bread wheat, from farm	0.16	0.60
Carrot, conventional, washed and packed, from field	0.03	0.11
Cucumber, standard	0.63	4.19
Oat, conventional, from farm	0.12	0.40
Onion	0.07	0.33
Peas, from farm	0.12	0.45
Potatoes, from farm	0.03	0.11
Rye, conventional, from farm	0.14	0.52
Soy bean, from farm	0.10	0.59
Spring Barley, conventional, from farm	0.13	0.47
Straw, from farm	0.00	0.00
Sugar beet, from farm	0.01	0.04
Tomato, standard	0.49	3.30
Wheat, conventional, from farm	0.13	0.50
Winter Barley, conventional, from farm	0.12	0.43
fish, ex harbour (per kg)		
Cod, ex harbour	0.38	1.13
Flatfish, ex harbour	1.03	3.04
Herring, ex harbour	0.18	0.54
Industrial fish, ex harbour	0.07	0.21
Mackerel, ex harbour	0.05	0.15
Mussels, ex harbour	0.01	0.04
Norway lobster, ex harbour	6.49	19.14
Sand eel, ex harbour	0.05	0.16
Shrimp/prawn, ex harbour	0.92	2.63
Trout (standard), from trout pond farm	0.44	1.60
supermarket, cooling counter (per kg)		
Beef fillet (oksefillet), fresh, in supermarket	10.32	41.29
Beef flanchet (flanchet), fresh, in supermarket	5.16	20.63
Beef foreend (bov), fresh, in supermarket	5.66	22.65
Beef knuckle shank (okseskank), fresh, in superm.	1.50	3.81
Beef minced meat (oksesmåkød), fresh, in superm.	1.60	4.07
Beef outside (okseyderlår), fresh, in supermarket	5.15	20.57

Beef round (okseklump), fresh, in supermarket	5.10	20.41
Beef steak (oksetyksteg), fresh, in supermarket	9.13	36.52
Beef steak (oksetyndsteg), fresh, in supermarket	9.13	36.52
Beef tenderloin (oksemørbrad), fresh, in superm.	15.66	62.62
Beef top round (okseinderlår), fresh, in superm.	9.75	38.98
Chicken, fresh, in supermarket	0.84	2.82
Cod fillet, fresh, in supermarket (no quotas)	0.86	2.63
Cod, fresh, in supermarket (no quotas)	0.39	1.15
Flatfish fillet, fresh, in supermarket (no quotas)	2.31	6.88
Flatfish, fresh, in supermarket (no quotas)	1.04	3.06
Ham (skinke), fresh, in supermarket	0.95	3.08
Herring fillet, fresh, in supermarket (no quotas)	0.39	1.20
Herring, fresh, in supermarket (no quotas)	0.19	0.56
Lobster, fresh, in supermarket (no quotas)	6.50	19.15
Mackerel fillet, fresh, in supermarket (no quotas)	0.15	0.57
Mackerel, fresh, in supermarket (no quotas)	0.06	0.17
Mussels, fresh, in supermarket (no quotas)	0.02	0.05
Pork minced meat (flæskesmåkød), fresh, in superm.	0.95	3.07
Pork minced meat (halssnitter), fresh, in superm.	0.96	3.09
Pork neck (svinekam), fresh, in superm.	0.95	3.08
Pork tenderloin (svinemørbrad), fresh, in superm.	0.94	3.04
Shrimps, fresh, in supermarket (no quotas)	0.92	2.65
Steaky bacon (brystflæsk), fresh, in superm.	0.95	3.08
supermarket, freesing counter (per kg)		
Bread, wheat, frozen, in supermarket	0.20	0.89
Chicken, frozen, in supermarket	0.92	3.27
Cod fillet, frozen, in supermarket (no quotas)	0.93	3.01
Flatfish fillet, frozen, in supermarket (no quota)	2.38	7.26
Herring fillet, frozen, in supermarket (no quota)	0.46	1.64
Mackerel fillet, frozen, in supermarket (no quota)	0.20	0.88
Rolls, frozen, in supermarket	0.21	0.97
Shrimps, frozen, in supermarket (no quota)	2.98	9.29
Trout, frozen, in supermarket (market regulated)	0.82	3.99
supermarket, bread etc. (per kg)		
Bread, rye, fresh, in supermarket	0.13	0.53
Bread, wheat, fresh, in supermarket	0.14	0.58
Flour, rye, in supermarket	0.17	0.60
Flour, wheat, in supermarket	0.18	0.70
Oat flakes, in supermarket	0.15	0.66
Potatoes, in supermarket	0.04	0.14
Rape seed oil, in supermarket	0.75	2.48
Rolls, fresh, in supermarket	0.15	0.66
Sugar, in supermarket	0.11	0.57

1.4 Energy & fuels

Table 1.14 Energy & fuels

Energy & fuels, Idemat 2015	eco-costs (euro)	carbon footprint (CO2 equ.)
electricity (100 MW)		
Electricity from offshore windmill 2 MW (Danish coast)	0.27	0.5
PV panel on roof 3KWp (ribbon-Si, Switserland)	0.71	2.1
Electricity General (UCTE)	2.60	14.0
Electricity Industrial Western Europe (ENTSO-E)	2.59	14.0
Electricity Low Voltage, domestic use General	2.74	14.7
Electricity Low Voltage, domestic use Netherlands	2.93	19.4
heat (100 MW)		
Industrial Heat, General	1.17	6.3
Domestic Heat, General	1.35	7.2
Energy gas, condensing, domestic (=heat)	1.27	7.5
Energy oil (=heat)	1.49	9.1
fuel (kg)		
biodiesel (palm oil methyl ester)	0.56	0.9
biodiesel (rape methyl ester)	0.60	2.0
biodiesel (soyabean ester, USA)	0.32	1.2
ethanol (from swedish wood)	0.16	0.6
petrol (85% ethanol from swedish wood)	0.17	0.7
LPG (excluding combustion)	0.76	0.3
LPG including combustion	1.17	3.3
CNG (compressed natural gas) incl mat depl, excl. combustion	0.77	0.7
CNG (compressed natural gas) including combustion	1.14	3.4
Natural gas general EU for heat (excl mat depl. excl. combustion)	0.15	0.7
Natural gas general EU for heat (excl mat depl. incl. combustion)	0.53	3.4
Crude oil General (excl. combustion)	0.78	0.3
Crude oil N-sea (GB) (excl. combustion)	0.71	0.0
Diesel low-sulphur (excluding combustion)	0.86	0.6
Diesel low-sulphur including combustion	1.28	3.8
Heavy fuel oil (excluding combustion)	0.83	0.5
Kerosene (excluding combustion)	0.85	0.6
Kerosene including combustion	1.27	3.7
Liquid propane/butane	0.87	0.7
Petrol (excluding combustion)	0.89	0.8
Petrol including combustion	1.31	3.9

For wind power in other areas of the world, see Section A.3. For PV panels in other areas of the world, see Section A.4

1.5 Transport

Table 1.15 Transport

Transport, Idemat 2015	eco-costs (euro)	carbon footprint (CO2 equ.)
Air traffic continental (min weight/volume ratio 0,167 ton/m3) (tkm)	0.614	1.70
Air traffic intercontinental (min weight/volume ratio 0,167 ton/m3) (tkm)	0.394	1.10
Air traffic continental (max weight/volume ratio 0,167 ton/m3) (m3.km)	0.102	0.28
Air traffic intercontinental (max weight/volume ratio 0,167 ton/m3) (m3.km)	0.066	0.18
Train, freight diesel USA (tkm)	0.024	0.06
Train, freight, Europe (tkm)	0.015	0.05
Tractor (tkm)	0.158	0.39
Truck+container, 28 tons net (min weight/volume ratio 0,41 ton/m3) (tkm)	0.025	0.07
Truck+trailer 24 tons net (min weight/volume ratio 0,32 ton/m3) (tkm)	0.029	0.08
Truck+container, 28 tons net (max weight/volume ratio 0,41 ton/m3) (m3.km)	0.010	0.03
Truck+trailer 24 tons net (max weight/volume ratio 0,32 ton/m3) (m3.km)	0.009	0.03
Truck Euro 5 (km)	0.346	0.99
Car, diesel (km)	0.069	0.20
Car, lpg (km)	0.077	0.21
Car, petrol (km)	0.072	0.21
Car extra tonne per 100km (100 t.km)	0.032	0.09
Coach, diesel (km)	0.372	0.96
Delivery van, 5m3 < 3.5 t (km)	0.106	0.28
lorry 16 - 32 t Euro 5 (km)	0.282	0.80
lorry 3.5 - 7.5 t Euro 5 (km)	0.129	0.37
lorry 7.5 - 16 t Euro 5 (km)	0.216	0.62
Motorbike (km)	0.063	0.19
Scooter, Moped (km)	0.043	0.13
Scooter, Moped, extra tonne per 100km (100 t.km)	0.116	0.35
Barge (10 t.km)	0.189	0.52
Bulk carrier (100 t.km)	0.436	0.87
Coaster (100 t.km)	0.579	1.15
Container ship (min weight/volume ratio 0,84 ton/m3) (100 t.km)	0.436	0.87
Tanker (100 t.km)	0.239	0.46
Container ship (max weight/volume ratio 0,84 ton/m3) (100 m3.km)	0.366	0.73

Distances over land can be found using Google Maps. For over water, see http://www.sea-distances.org/

2 Eco-based materials selection

The charts in this chapter were made using the Cambridge Engineering Selector software, CES EduPack, in combination with the eco-costs database for the software (available on request for license holders of CES EduPack and CES Selector at the website www.grantadesign.com). Background information on the issue of 'eco-informed material choice' is given in (Ashby, 2009).
It must be mentioned here, that the software can generate many types of charts, too much to show in this LCA data guide. Only 4 types of charts were selected for this guide:

- eco-costs versus yield strength, to select materials with a high strength and a low eco-burden
- eco-costs versus Young's modulus, to select materials with high stiffness and a low eco-burden
- eco-costs versus density, to select materials with a low weight (e.g. for parts of vehicles: note that transport of more weight results in more eco-burden)
- eco-costs versus the market price of bulk materials (it says something of the potential EVR of the products made of these materials)

Note that the graphs have a logarithmic scale, so the differences in eco-costs are enormous: often more than a factor 10 within the same group of materials.

The optimum choice depends on the specific application of the material. This is explained below for elongation of a tie rod, and bending of a beam. For a comprehensive explaination see (Ashby, 2009).

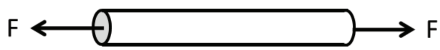

Figure 2.1 Elongation of a tie rod

Assume that a material has to be selected for a tie rod, that must be strong enough at the lowest possible eco-costs. The question now is how materials with a high yield strength and high eco-costs compare to materials with a low yield strength and low eco-costs.
In such a case the optimum material choice (Ashby, 2009) is determined by the lowest ratio

$$\frac{\text{eco-costs } (€/\text{m}^3)}{\text{yield strength (MPa)}}.$$

The same reasoning applies to the stiffness of the tie rod. The optimum material choice (Ashby, 2009) is determined by the lowest ratio

$$\frac{\text{eco-costs } (€/\text{m}^3)}{\text{young's modulus (GPa)}}.$$

The first equation results in a line of "equal eco-costs at equal strength" with a 1:1 slope as is depicted in the chart below. The same slope applies to "equal eco-costs at equal stiffness".

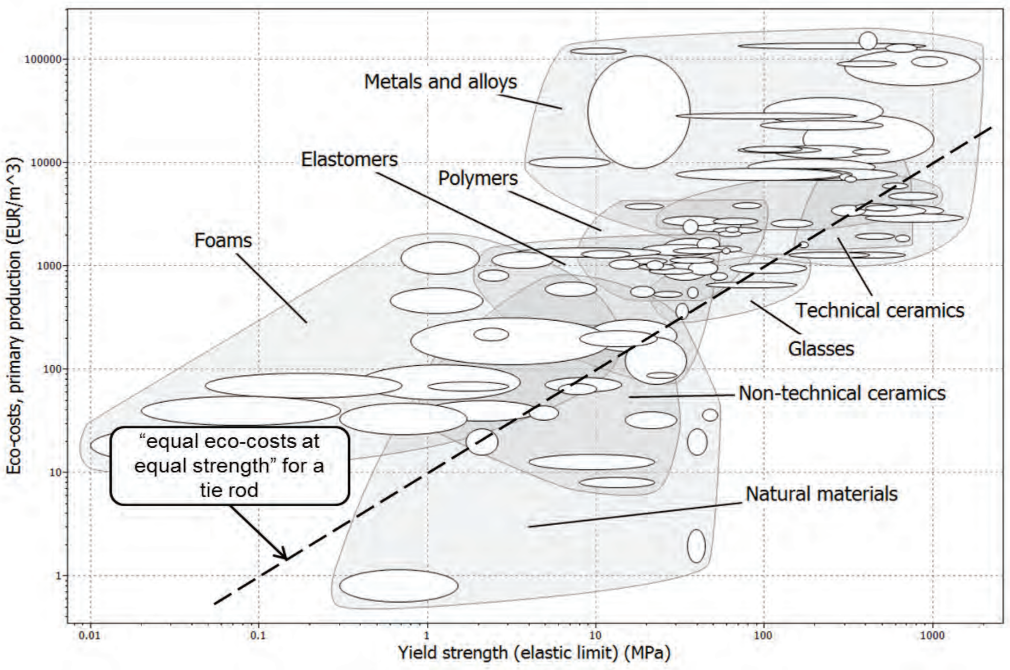

Figure 2.2 Eco-costs as a function of yield strength, and the line of "equal eco-costs at equal strength" for a tie rod (CES EduPack 2011)

In design, however, the bending characteristics of a beam are often more important.

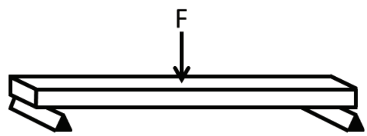

Figure 2.3 Bending of a beam

Assume that a material has to be selected for a beam, that must be strong enough and that must have as low as possible eco-costs. The question now is how materials with a high yield strength and high eco-costs (or density) compare to materials with a low yield strength and low eco-costs (or density).
In such a case the optimum material choice (Ashby, 2009) is determined by the ratio

$$\frac{\text{eco-costs } (€/\text{m}^3)}{[\text{yield strength (MPa)}]^{2/3}}.$$

The situation is different for the stiffness of the beam. The optimum material choice is then determined bij the ratio

$$\frac{\text{eco-costs } (€/m^3)}{[\text{young's modulus (GPa)}]^{1/2}}$$

This results in lines for “equal eco-costs at equal bending strenght” and “equal eco-costs at equal bending stiffness” as depicted in Figure 2.4 and 2.5. The slopes of the lines are 2:3 respectivily 1:2. Note that the same slopes apply for density versus yield strength and density versus young’s modulus.

Notes:

- The eco-costs of natural materials and of biodegradable plastics, which are shown in the charts, are “from cradle to the exit gate of production” (excluding End of Life). When these materials are burnt at the End of Life for production of heat or electricity, they will have a credit in LCA, see the tables in Chapter 1.
- The eco-costs of wood, cork, bamboo, minerals and stone which are shown in the charts, are for the case that the materials are applied locally (within a max. radius of 1000 km). The same applies for foams, brick, cement and concrete.
- The ranges which are indicated in the charts are caused by variations in the material type rather than the accuracy of the values
- **The data in this section are obsolete, since more recent data are available at https://www.ecocostsvalue.com/data-tools-books/ashby-charts/ , however, data have not changed drastically, so the charts can still be used for educational purposes.**

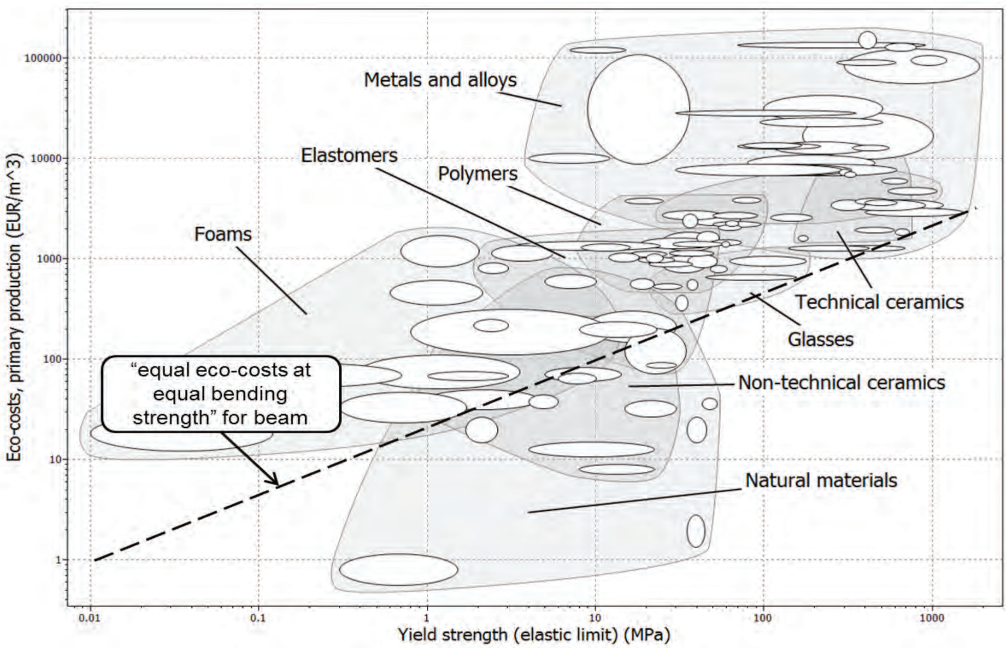

Figure 2.4 Eco-costs as a function of yield strength, and the line of "equal eco-costs at equal bending strength"" for a beam (CES EduPack 2011)

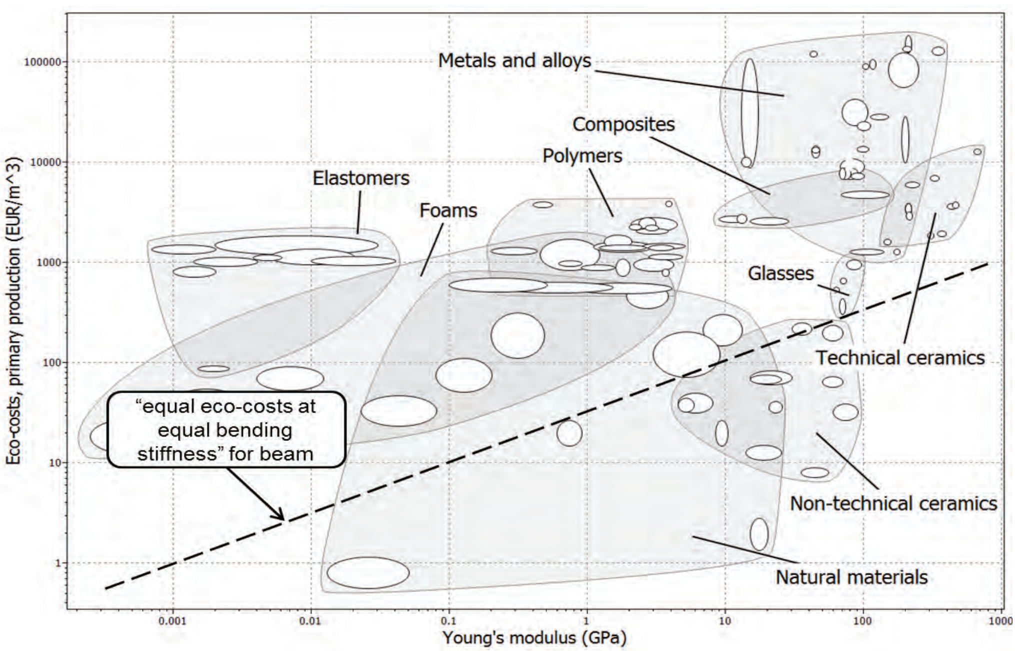

Figure 2.5 Eco-costs as a function of Young's modulus, and the line of "equal eco-costs at equal bending stiffness" for a beam (CES EduPack 2011)

2.1 General overview of materials (CES EduPack 2011)

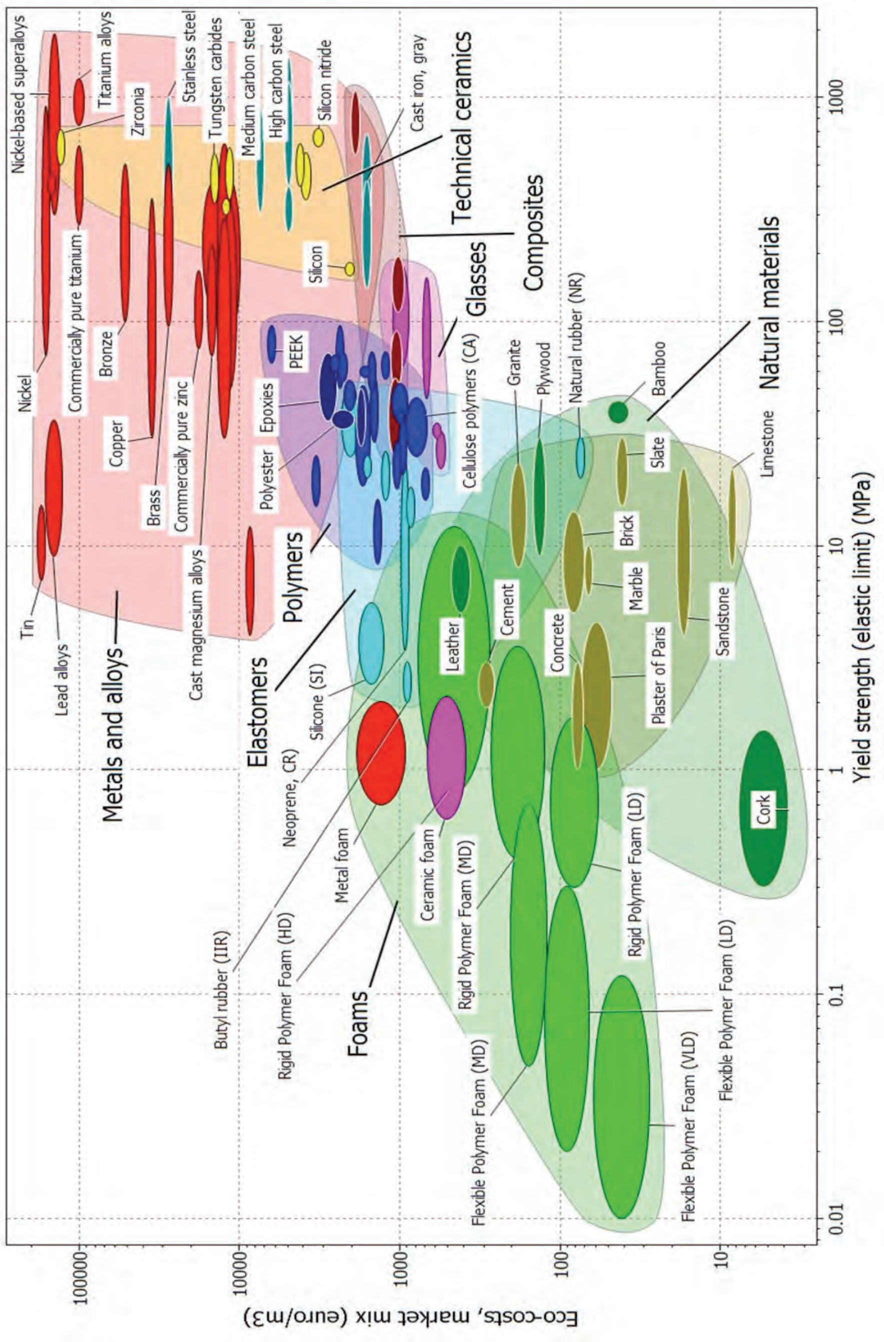

Figure 2.6 Eco-costs as a function of yield strength for classes of materials

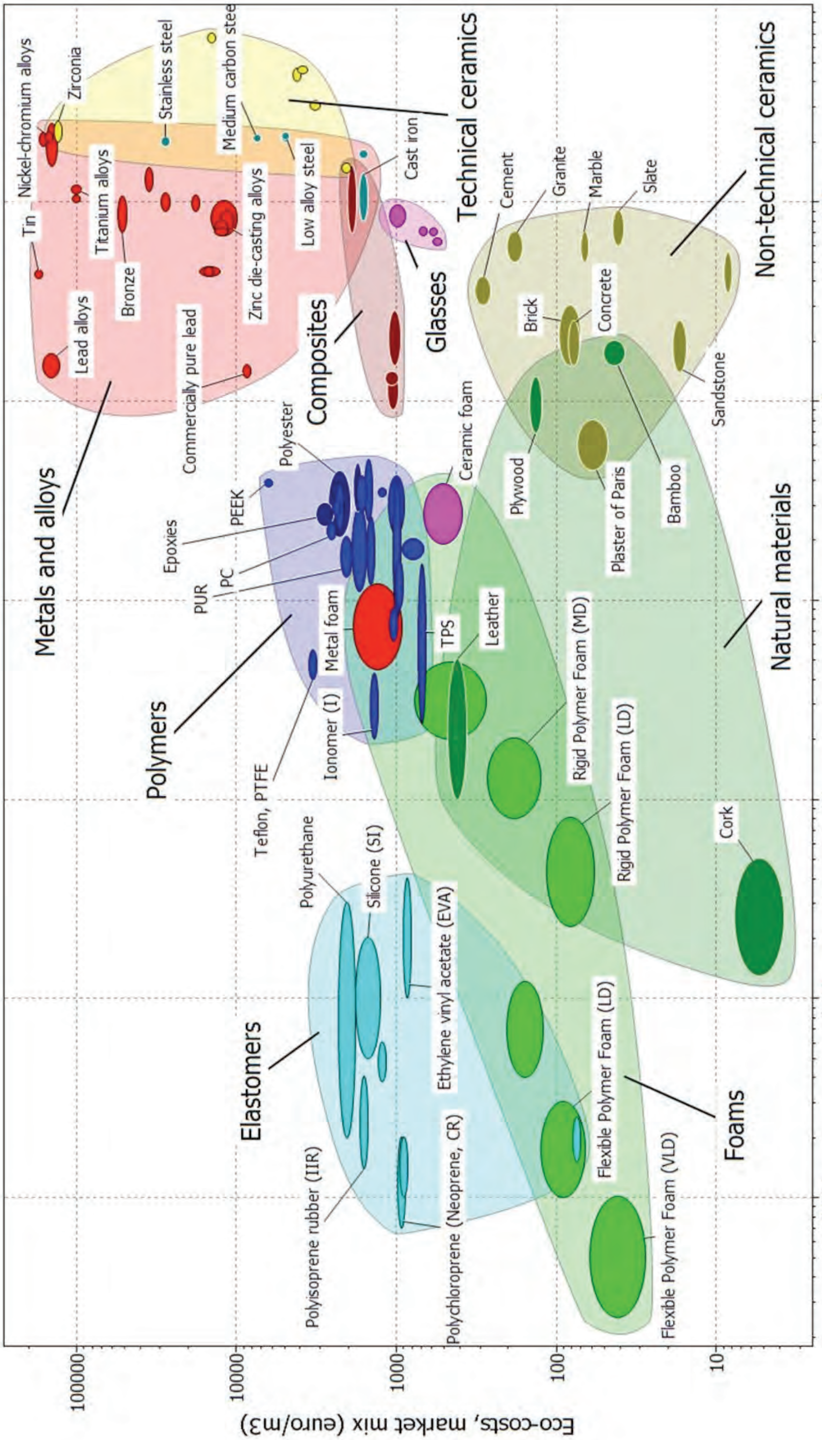

Figure 2.7 Eco-costs as a function of Youngs modulus for classes of materials

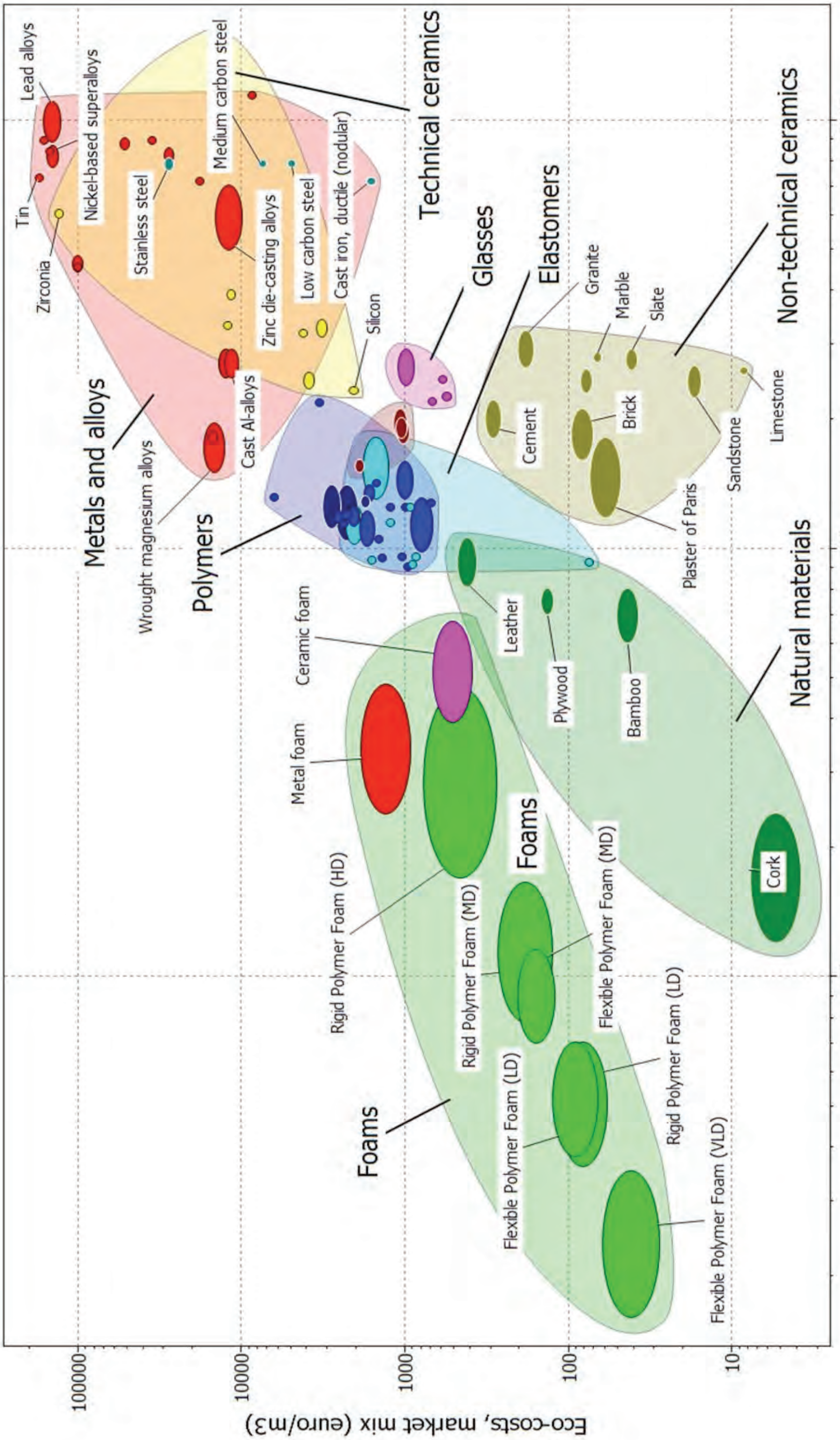

Figure 2.8 Eco-costs as a function of density for classes of materials

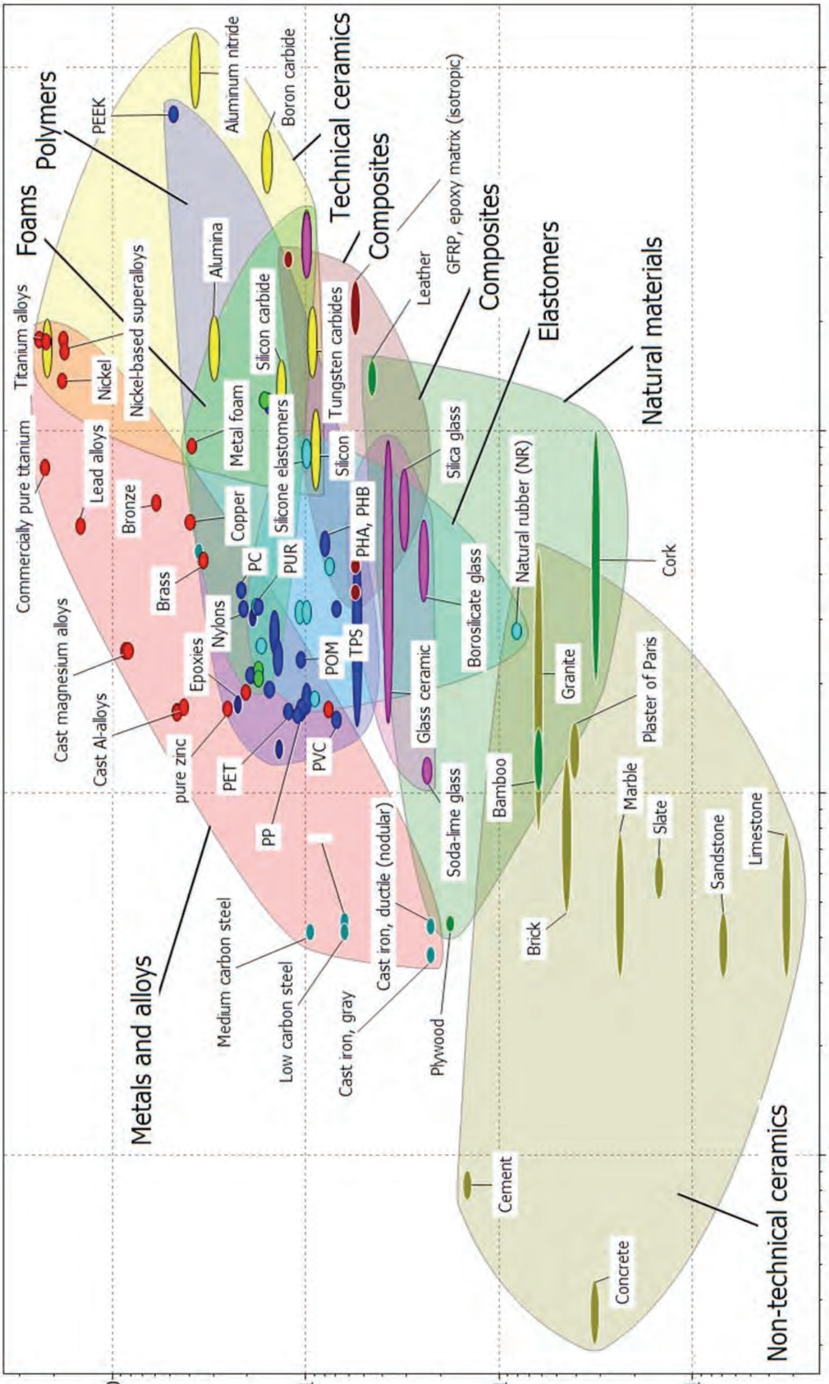

Figure 2.9 Eco-costs as a function of price for classes of materials

2.2 Metals

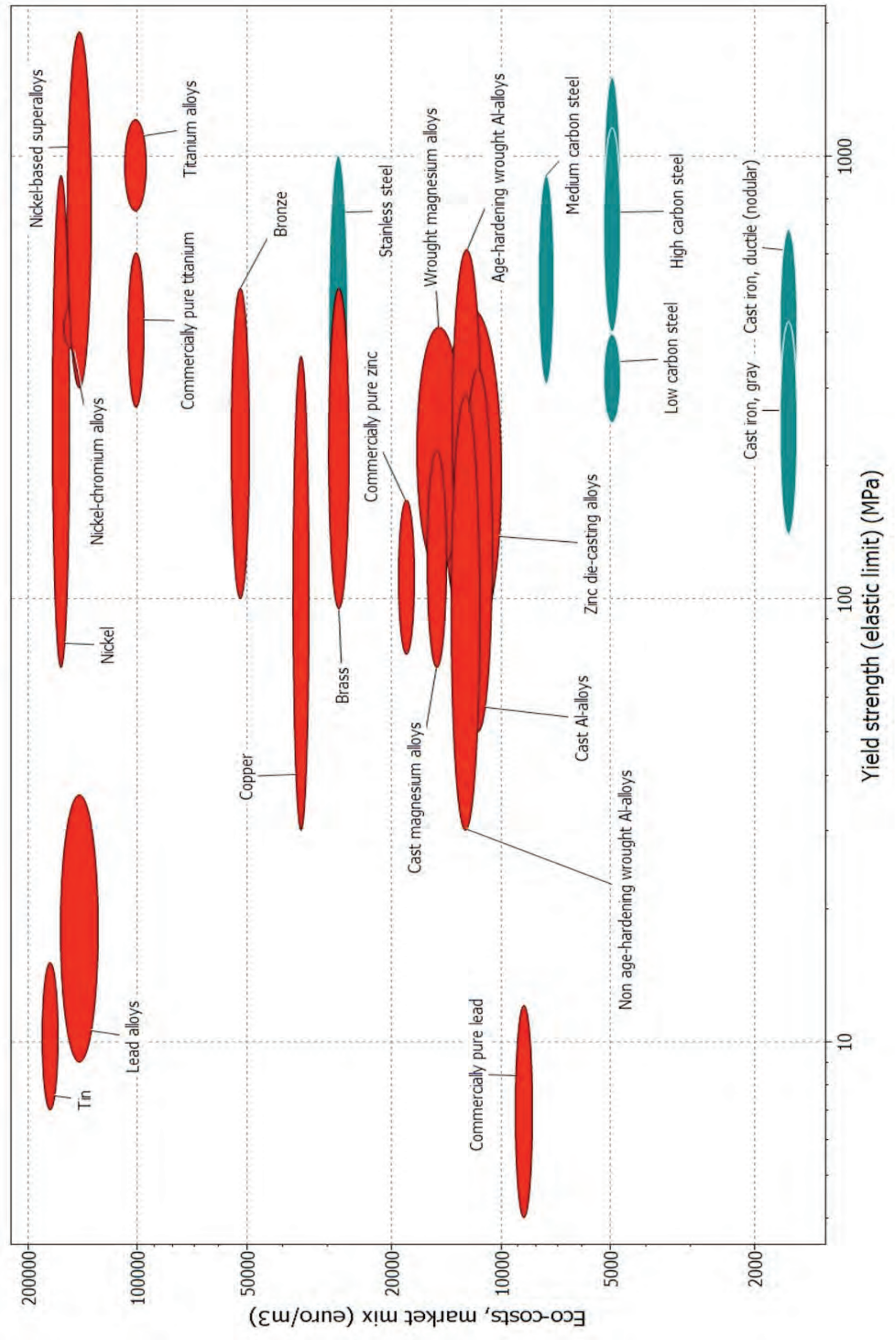

Figure 2.10 Eco-costs as a function of yield strength for metals

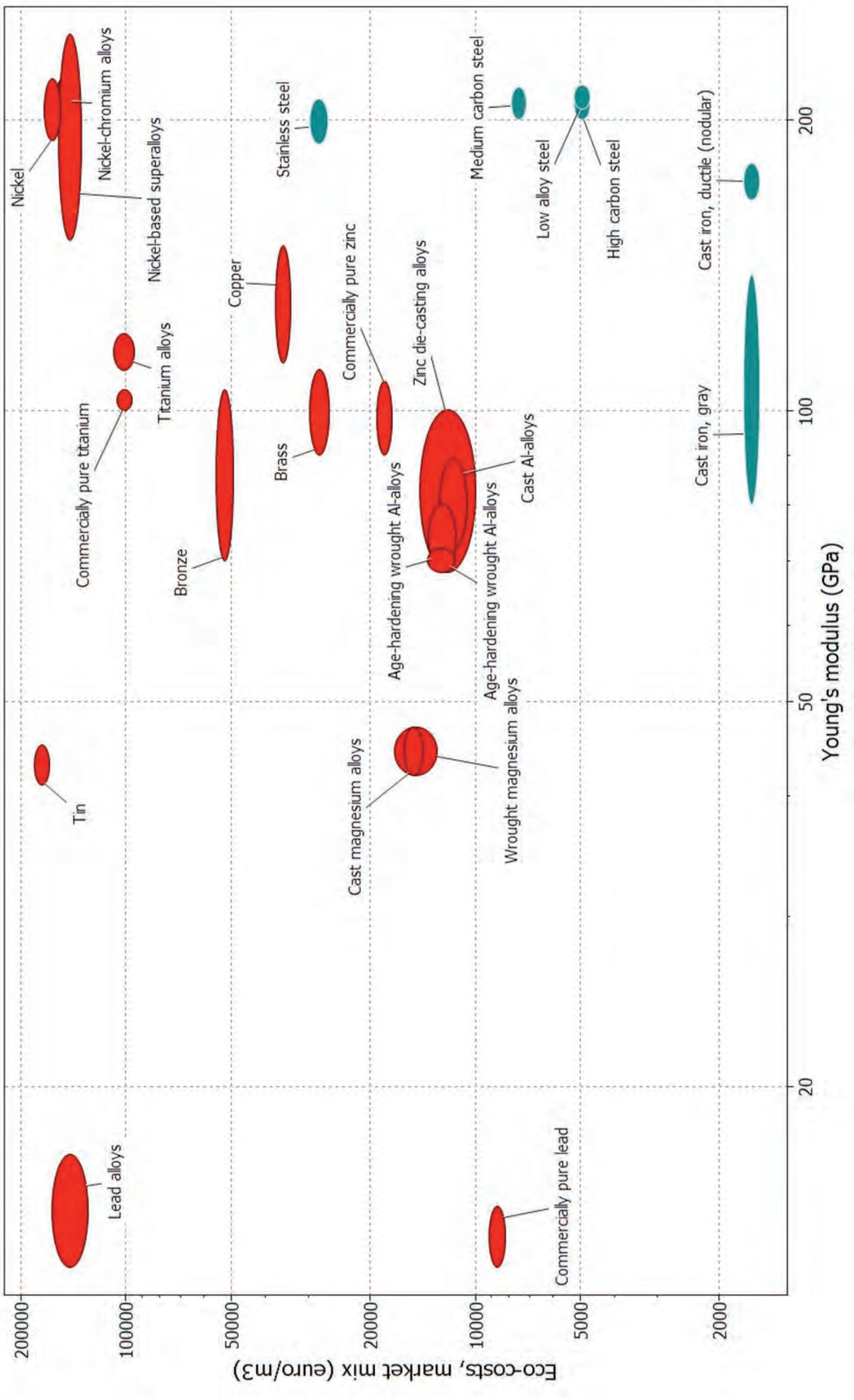

Figure 2.11 Eco-costs as a function of Youngs modulus for metals

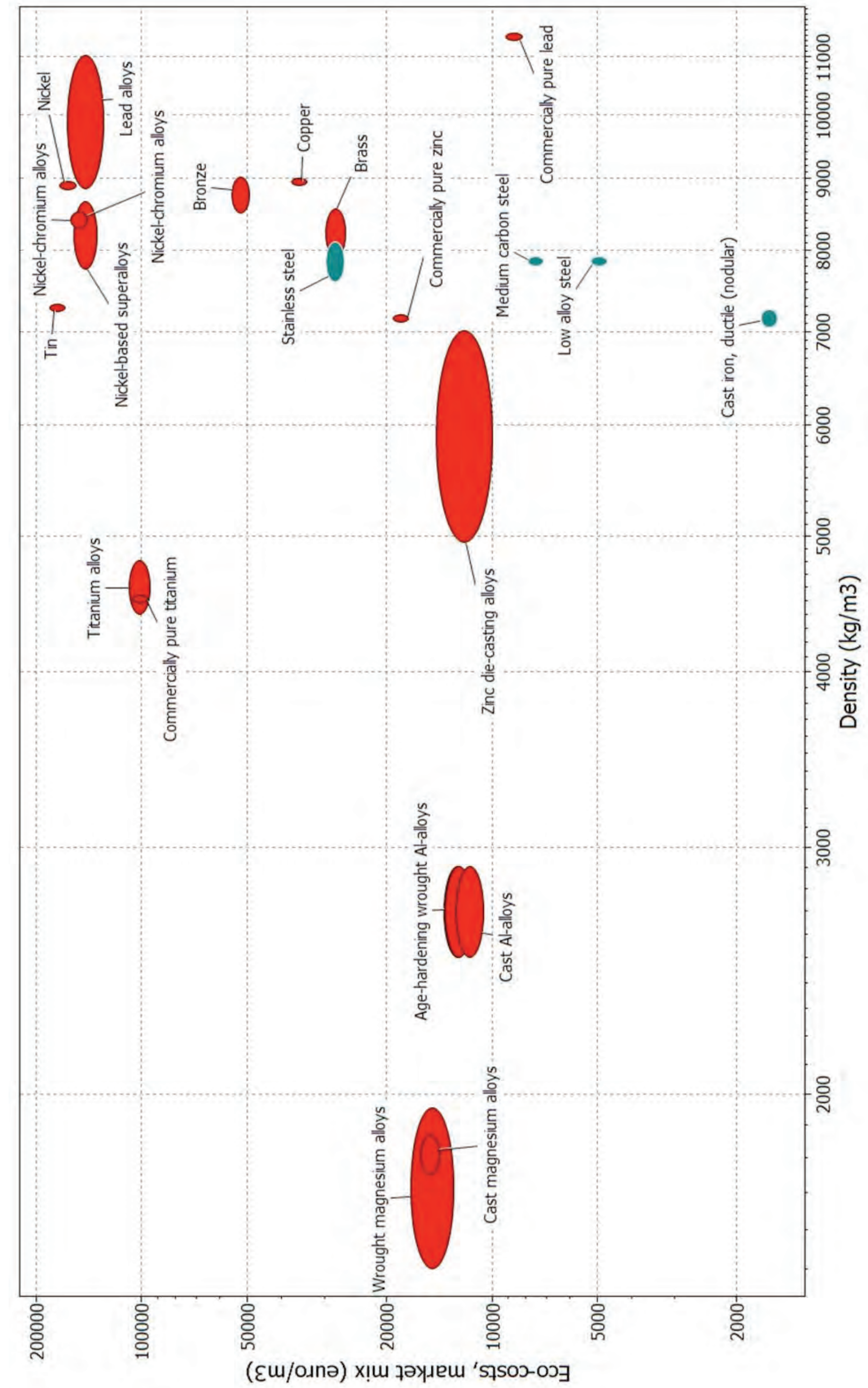

Figure 2.12 Eco-costs as a function of density for metals

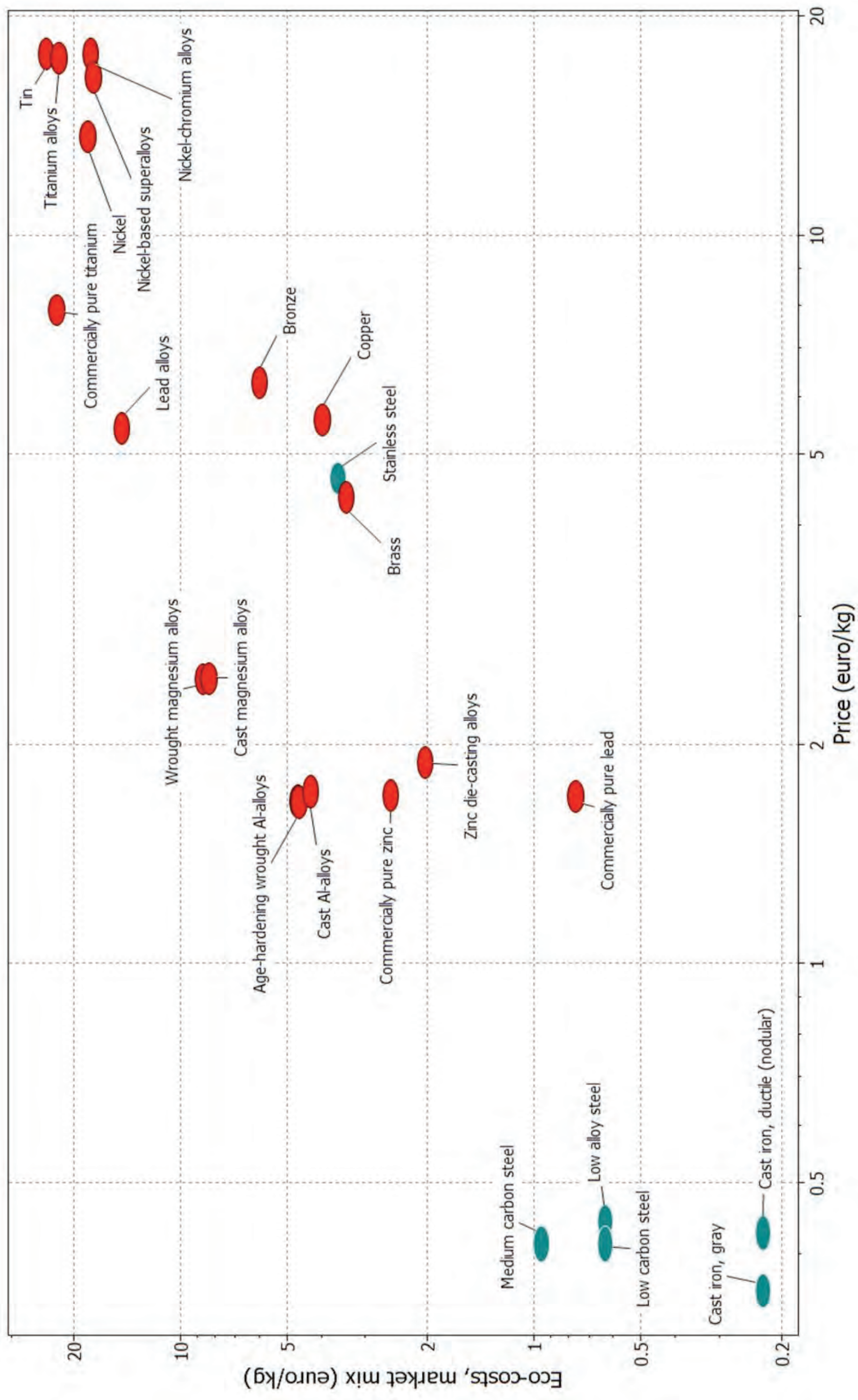

Figure 2.13 Eco-costs as a function of price for metals

2.3 Polymers

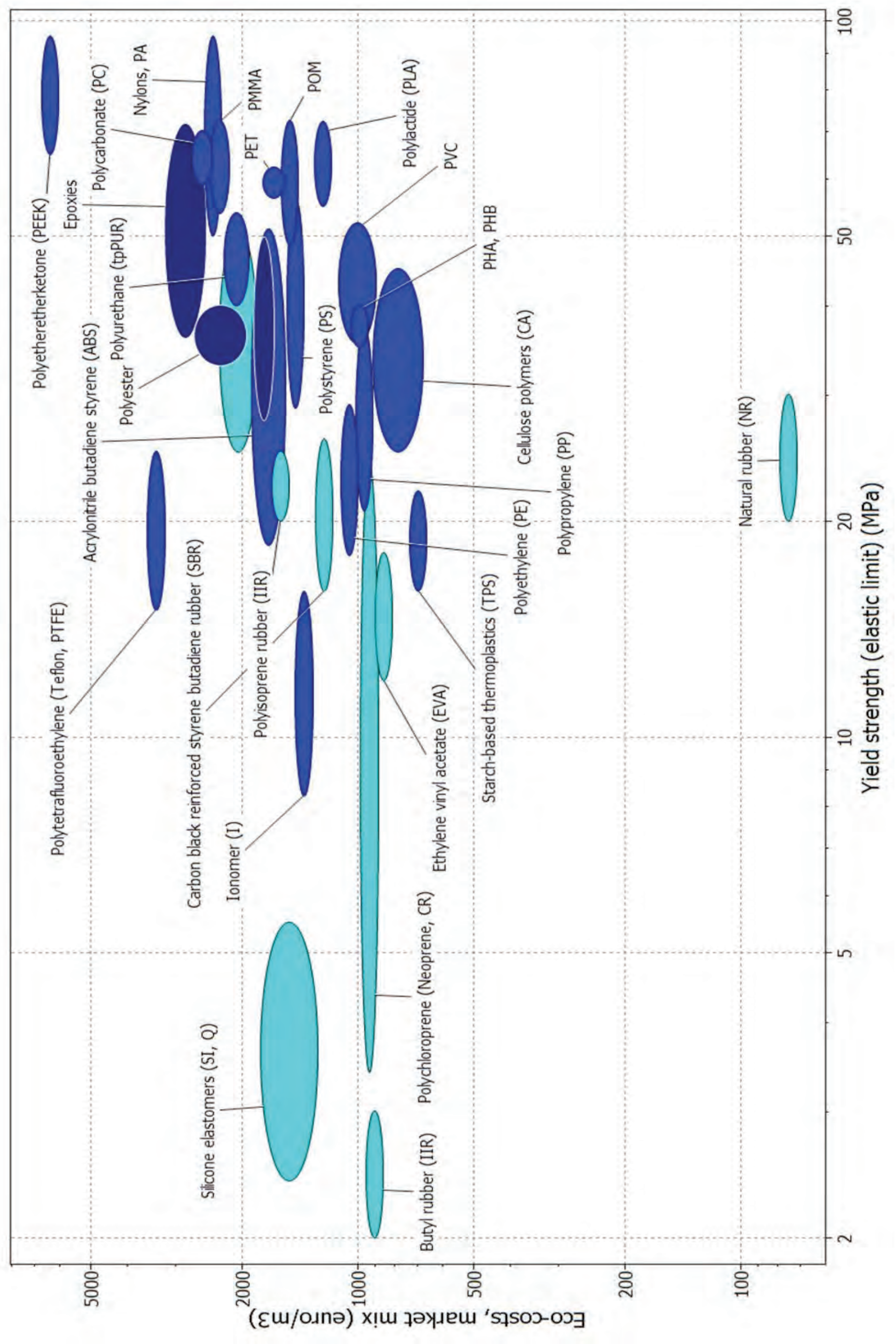

Figure 2.14 Eco-costs as a function of yield strength for polymers

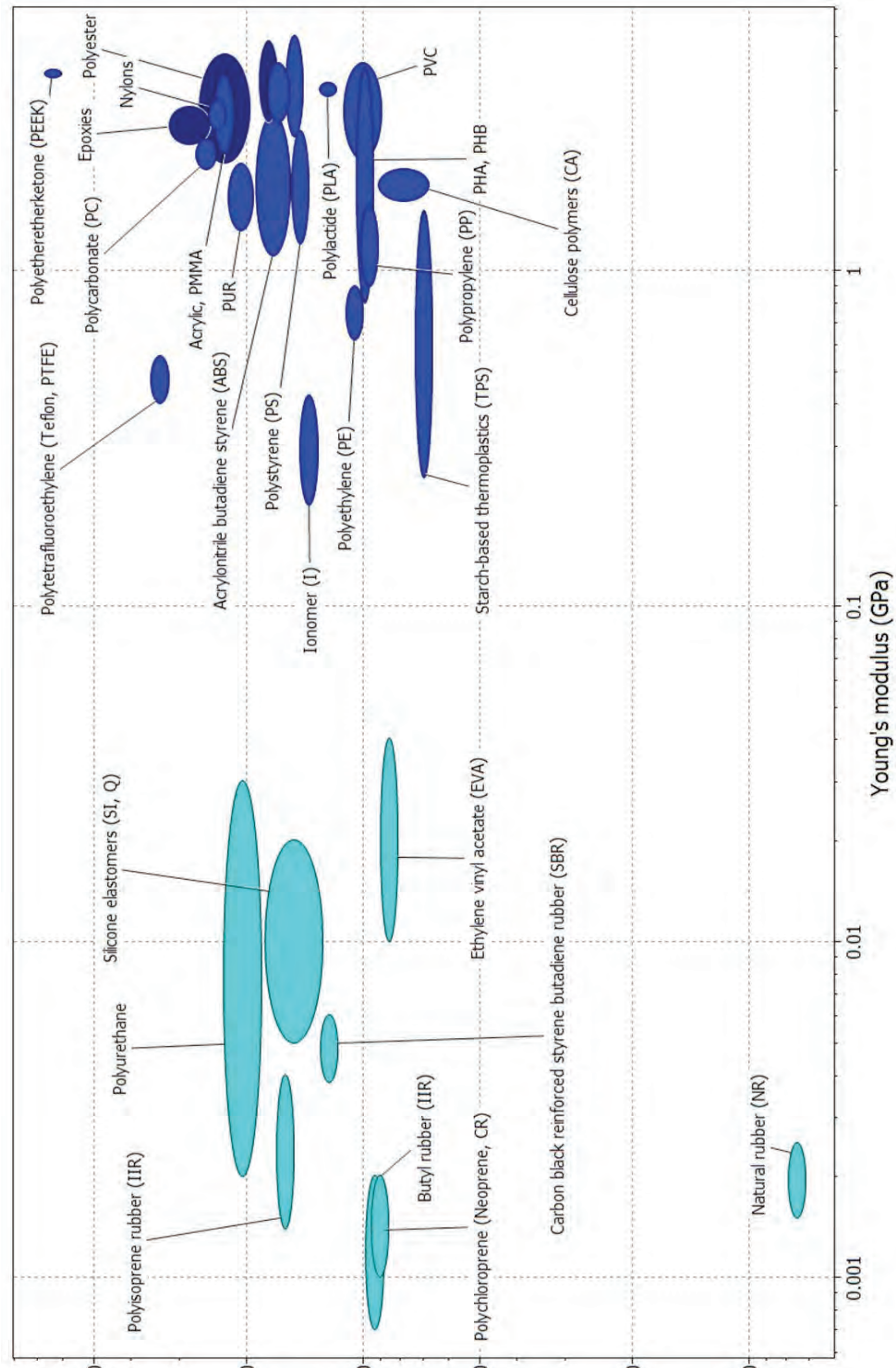

Figure 2.15 Eco-costs as a function of Youngs modulus for polymer

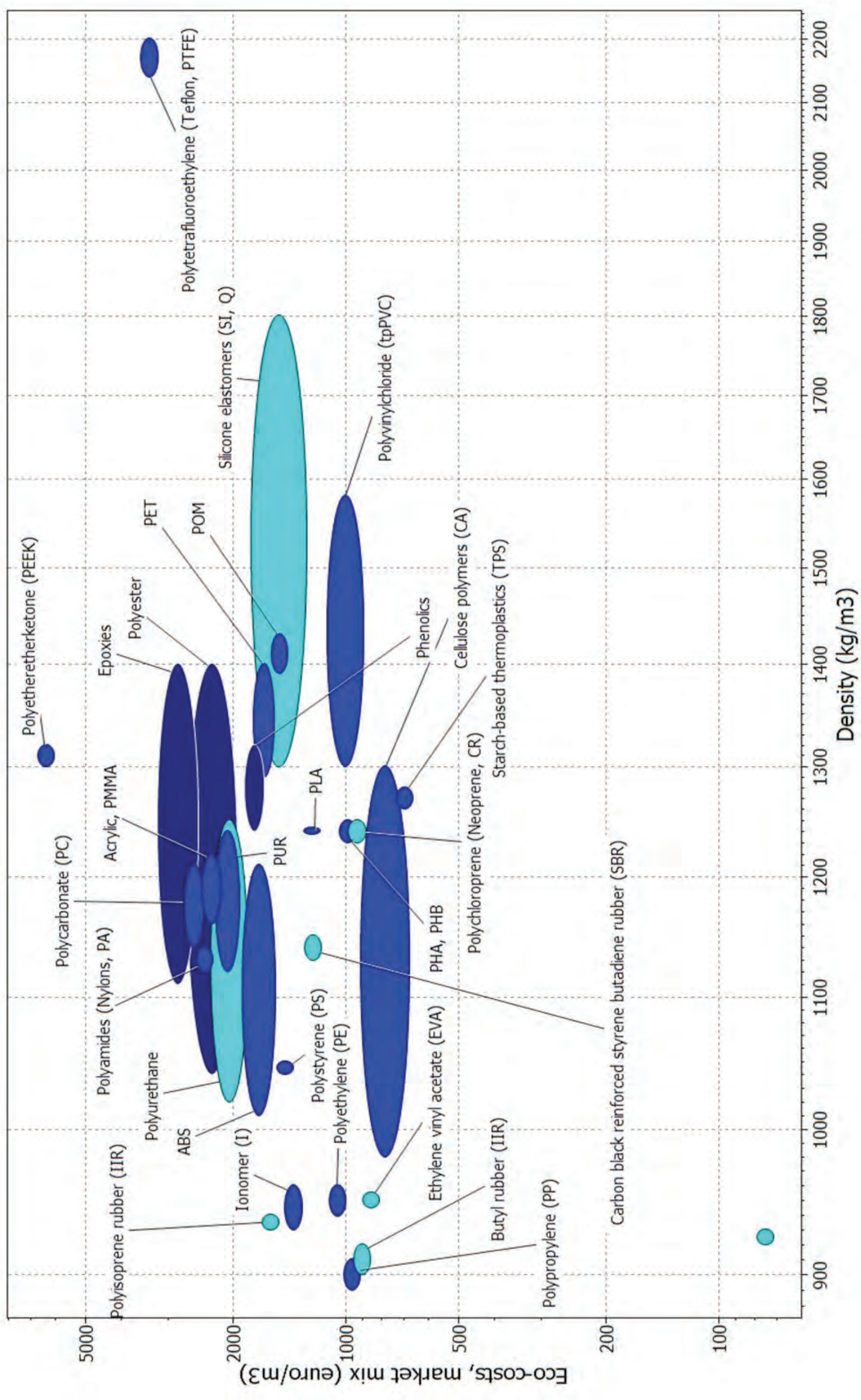

Figure 2.16 Eco-costs as a function of density for polymers

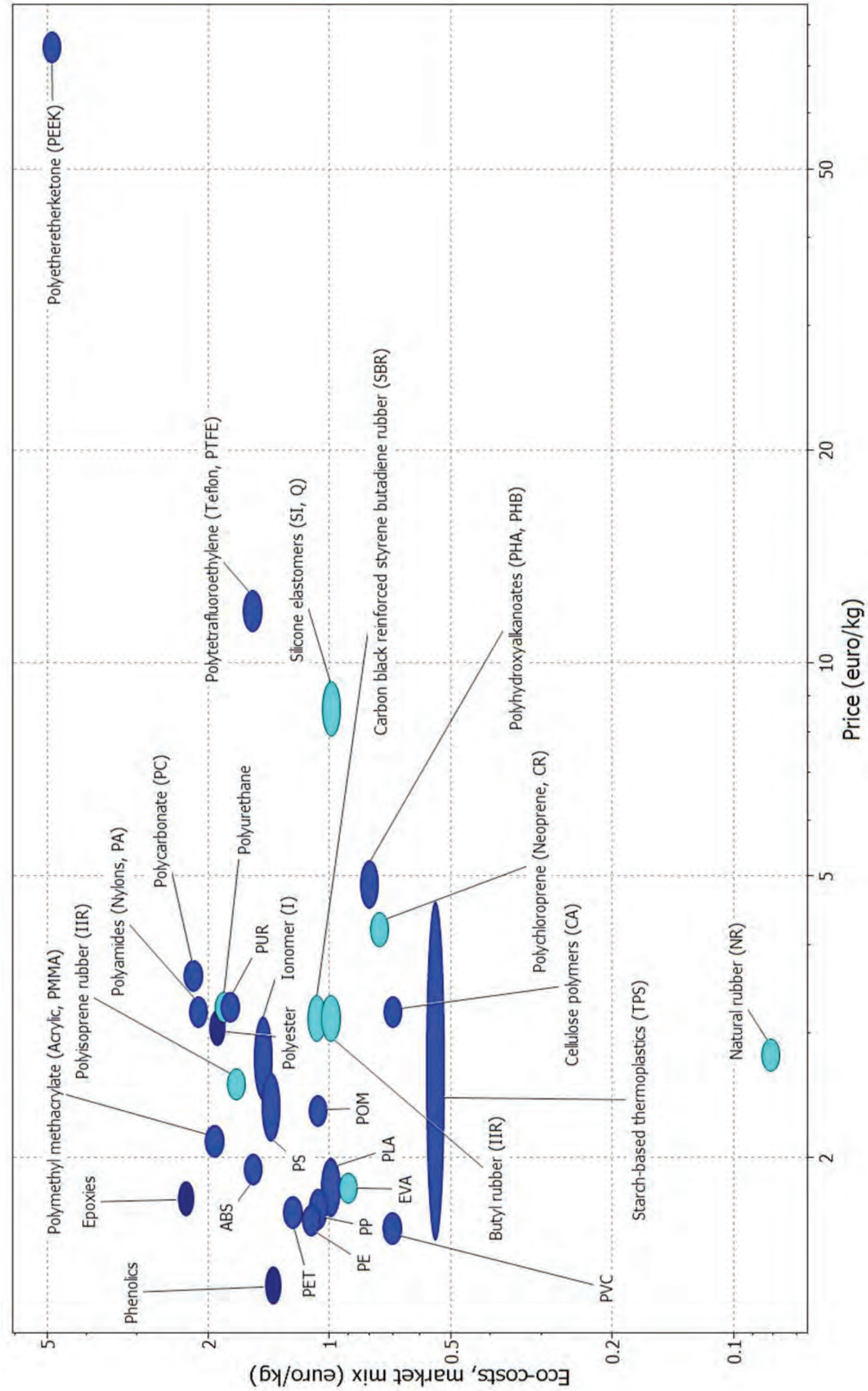

Figure 2.17 Eco-costs as a function of price for polymers

2.4 Tech Ceramics, Composites, Foams, Glass

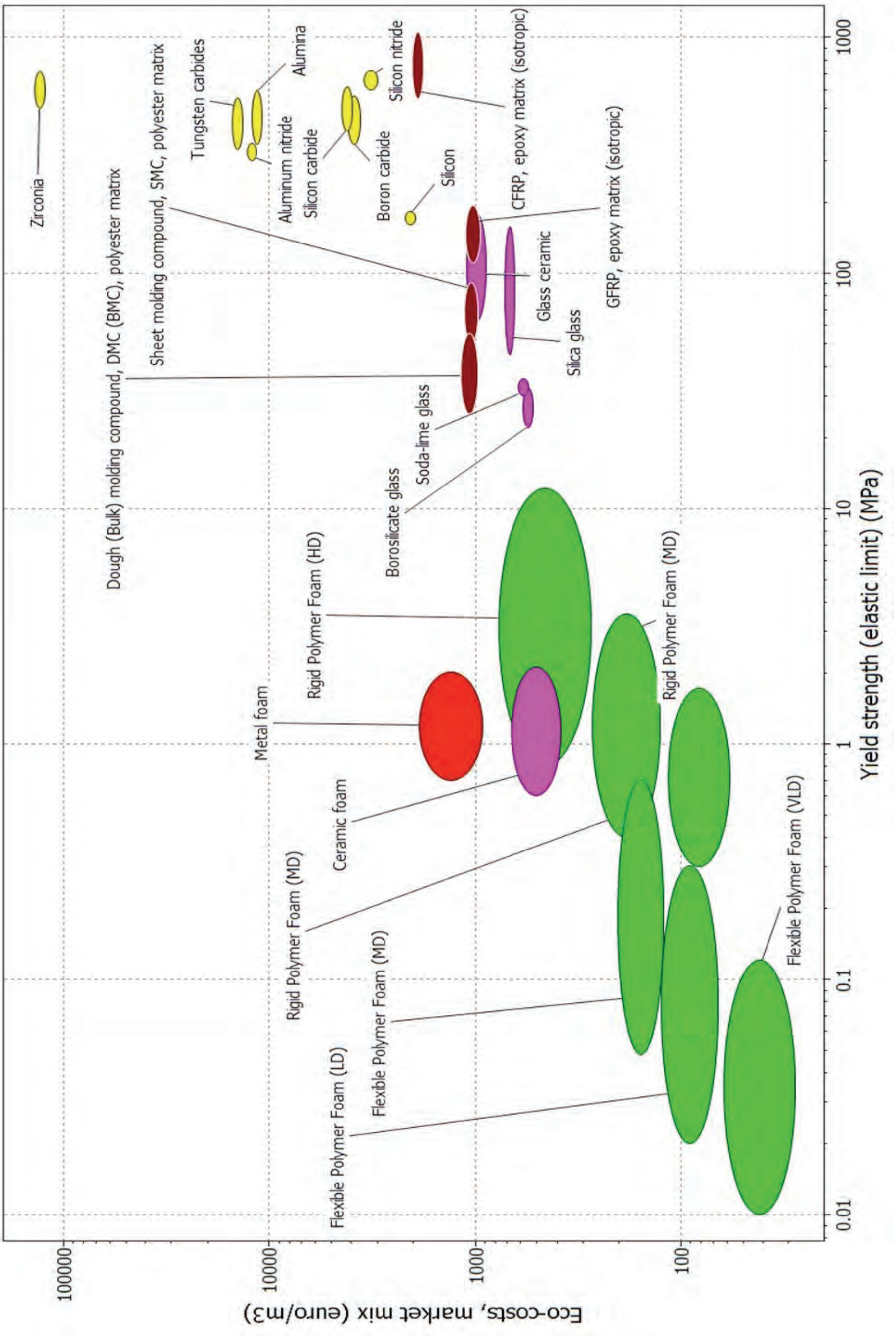

Figure 2.18 Eco-costs as a function of yield strength for tech. ceramics, composites, foams and glass

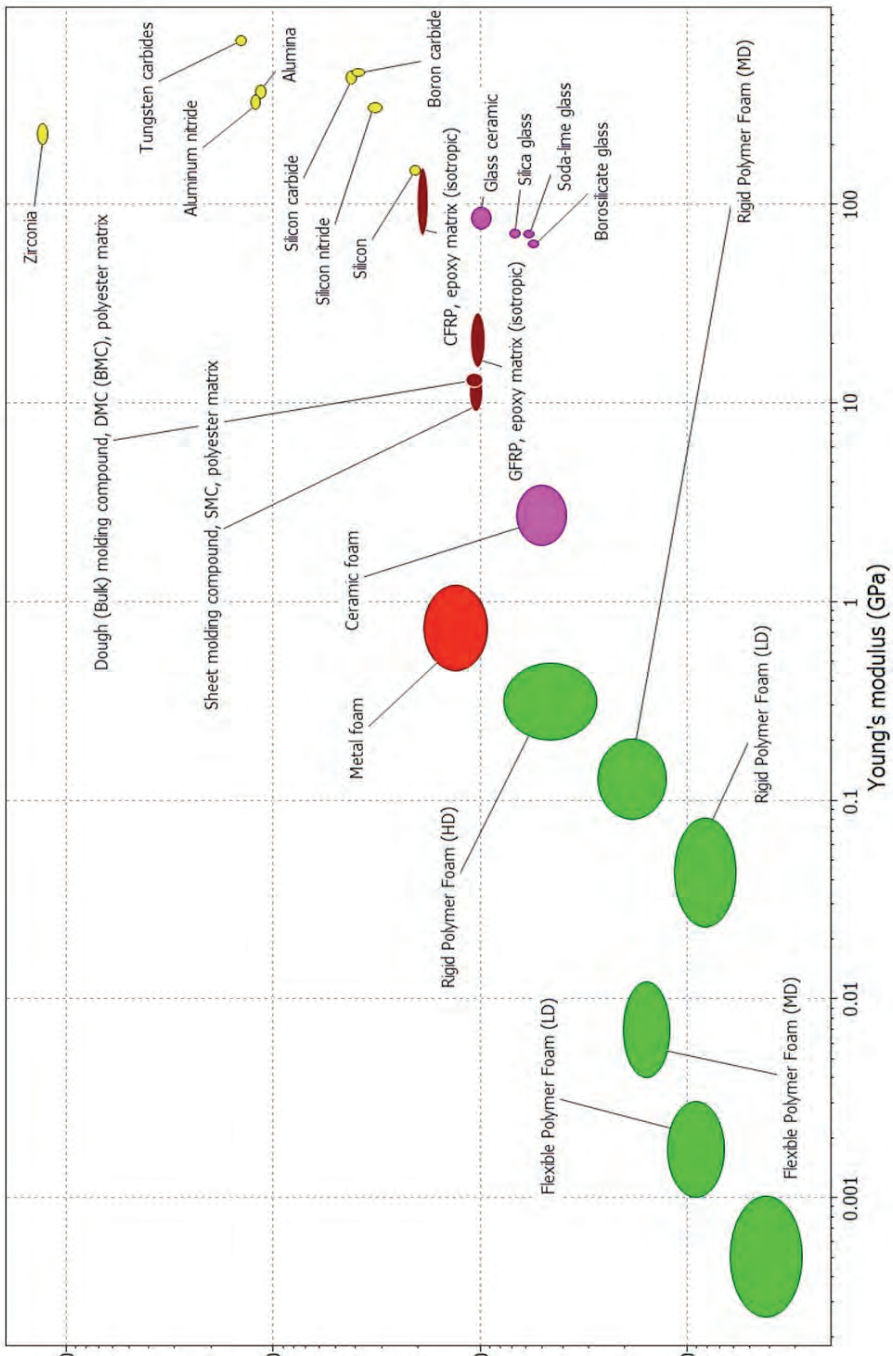

Figure 2.19 Eco-costs as a function of Youngs modulus for tech. ceramics, composites, foams and glass

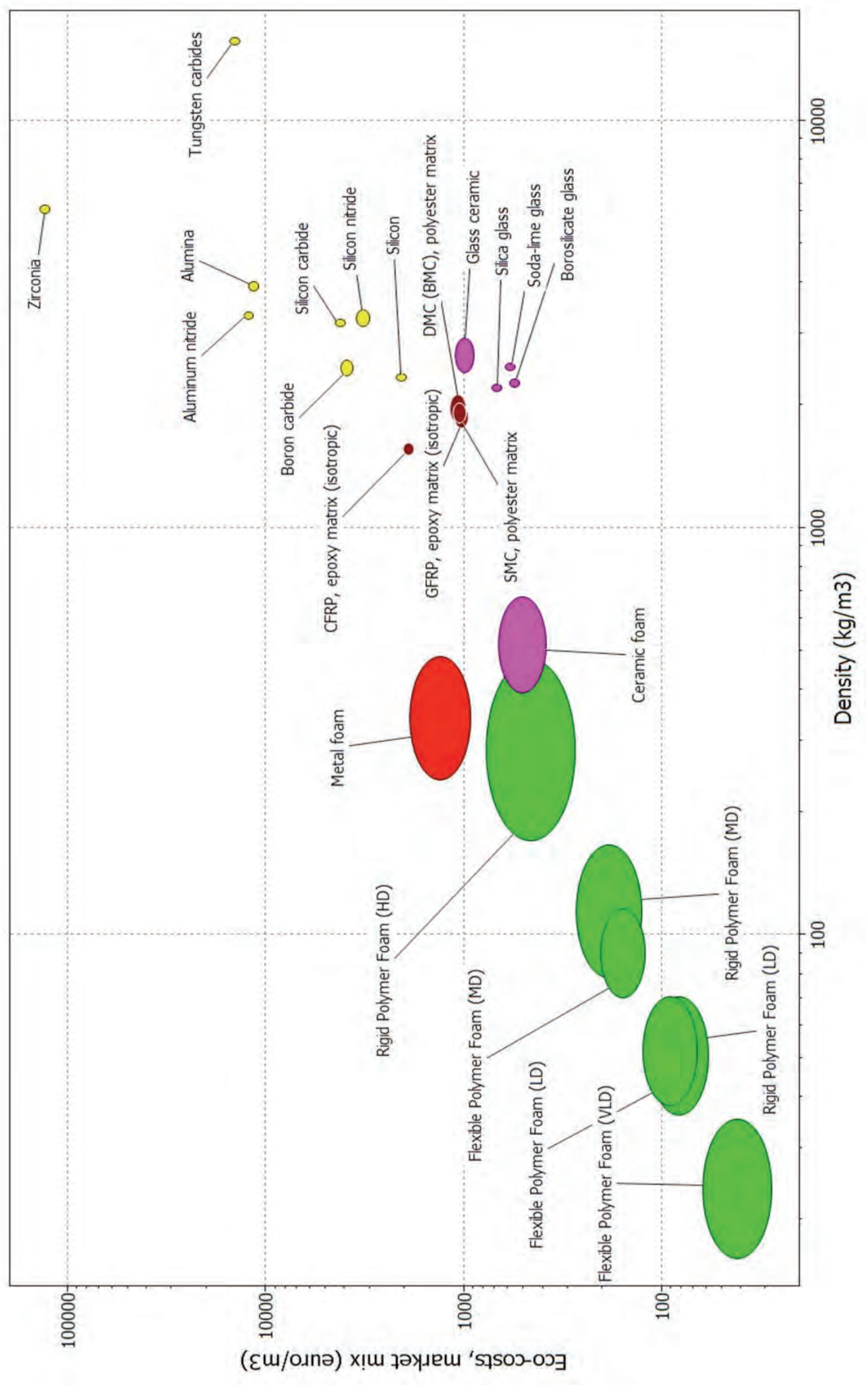

Figure 2.20 Eco-costs as a function of density for tech. ceramics, composites, foams and glass

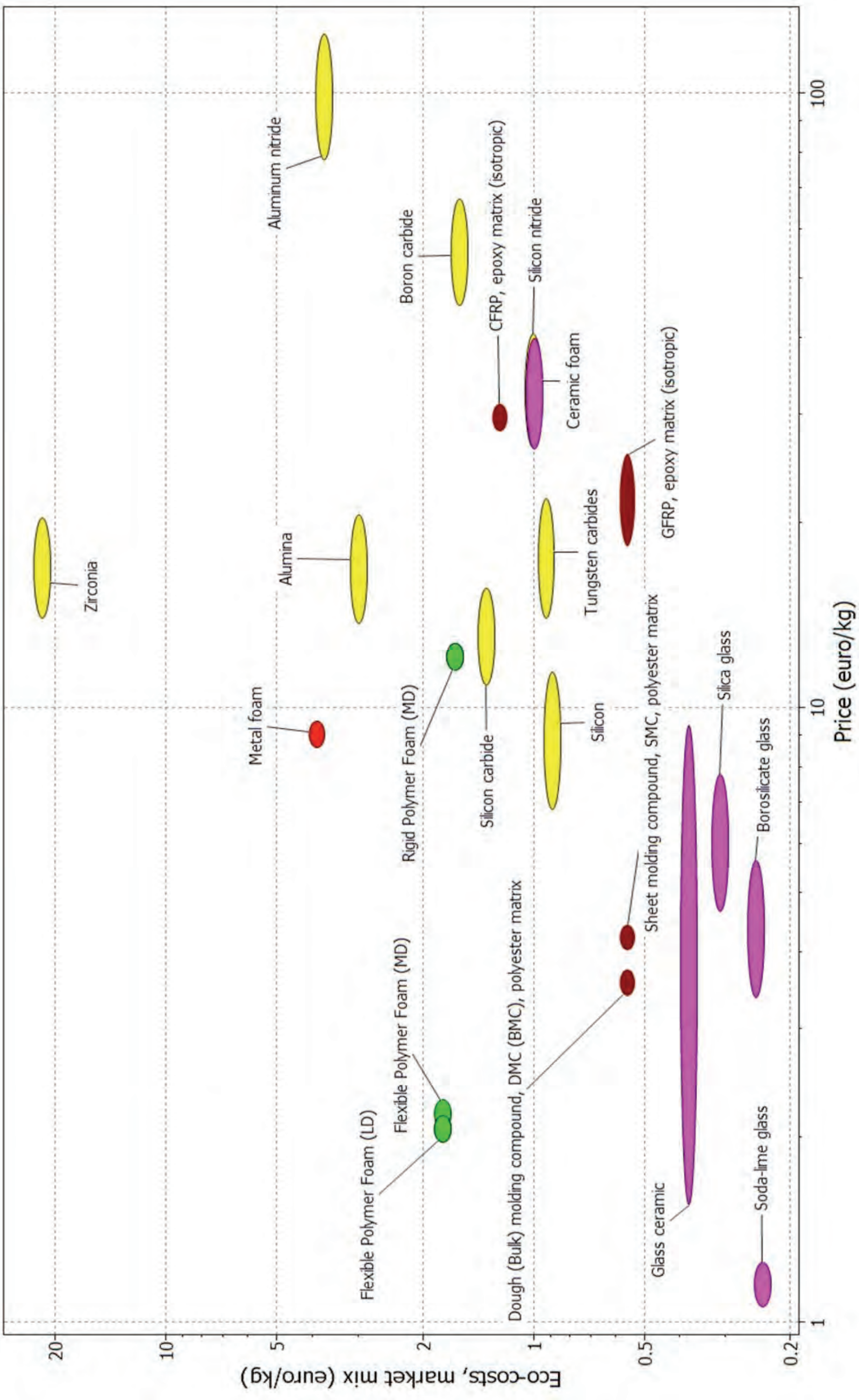

Figure 2.21 Eco-costs as a function of price for tech. ceramics, composites, foams and glass

2.5 Wood

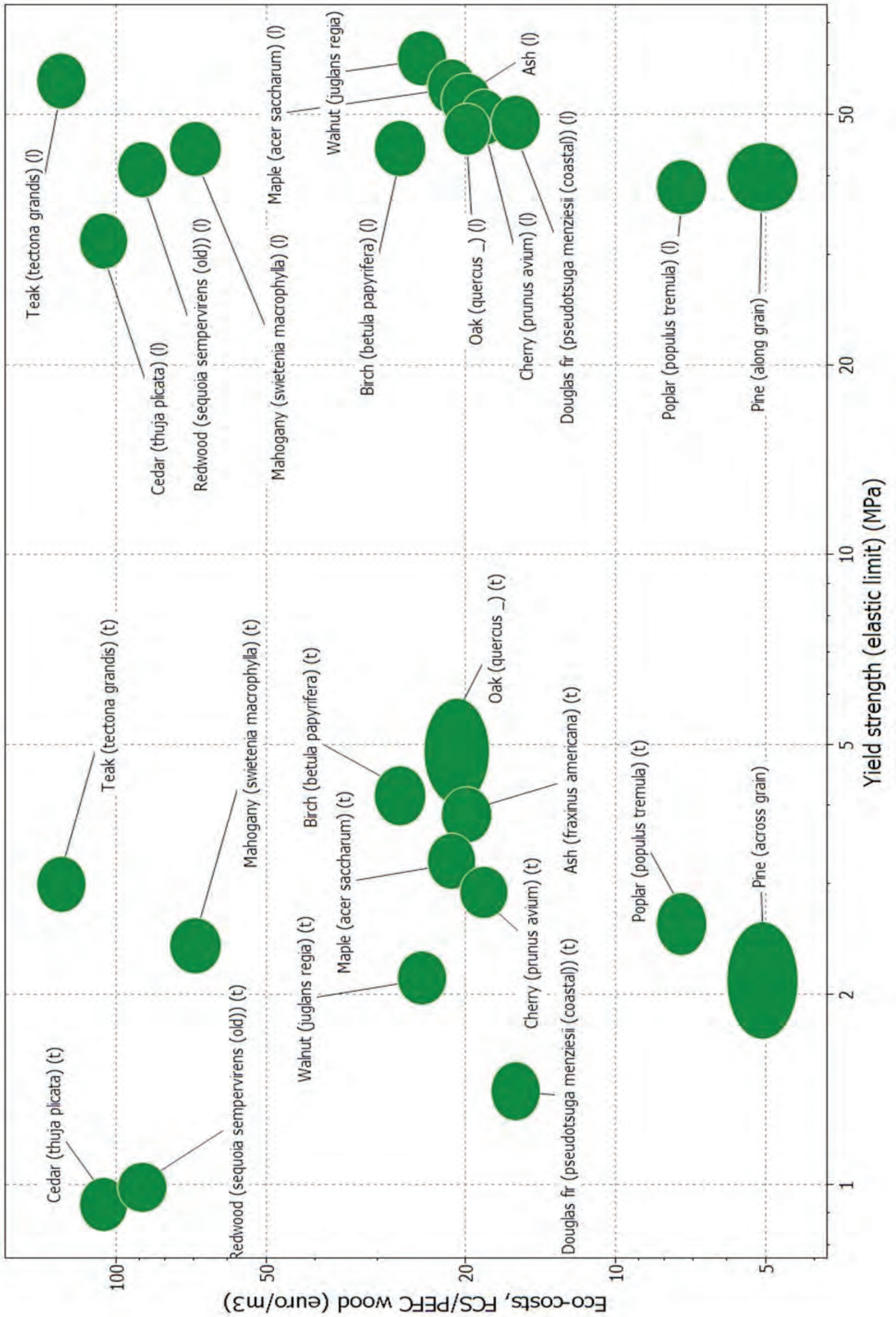

Figure 2.22 Eco-costs as a function of yield strength for wood (l = longitudinal, t = transversal)

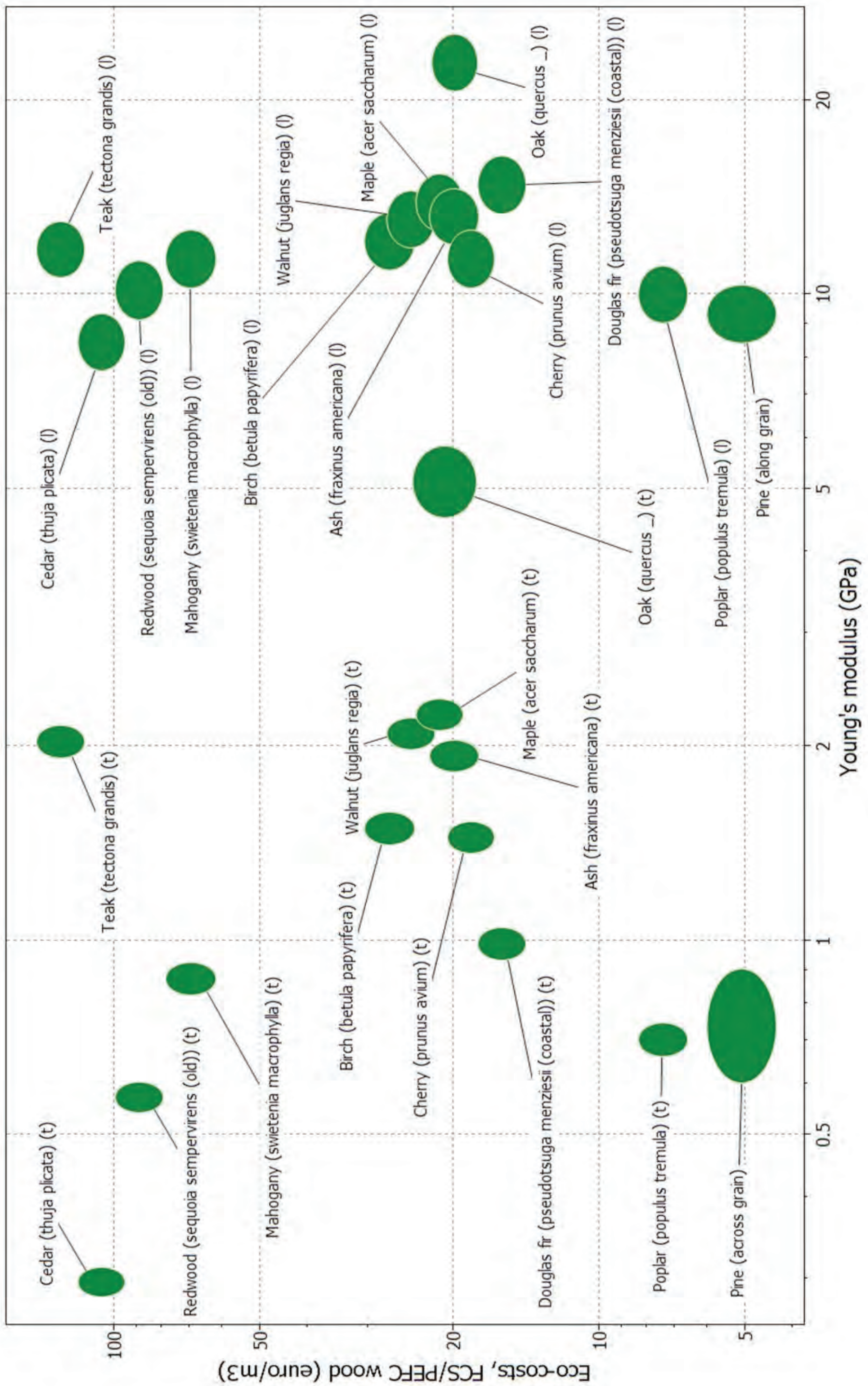

Figure 2.23 Eco-costs as a function of Youngs modulus for wood (l = longitudinal, t = transversal)

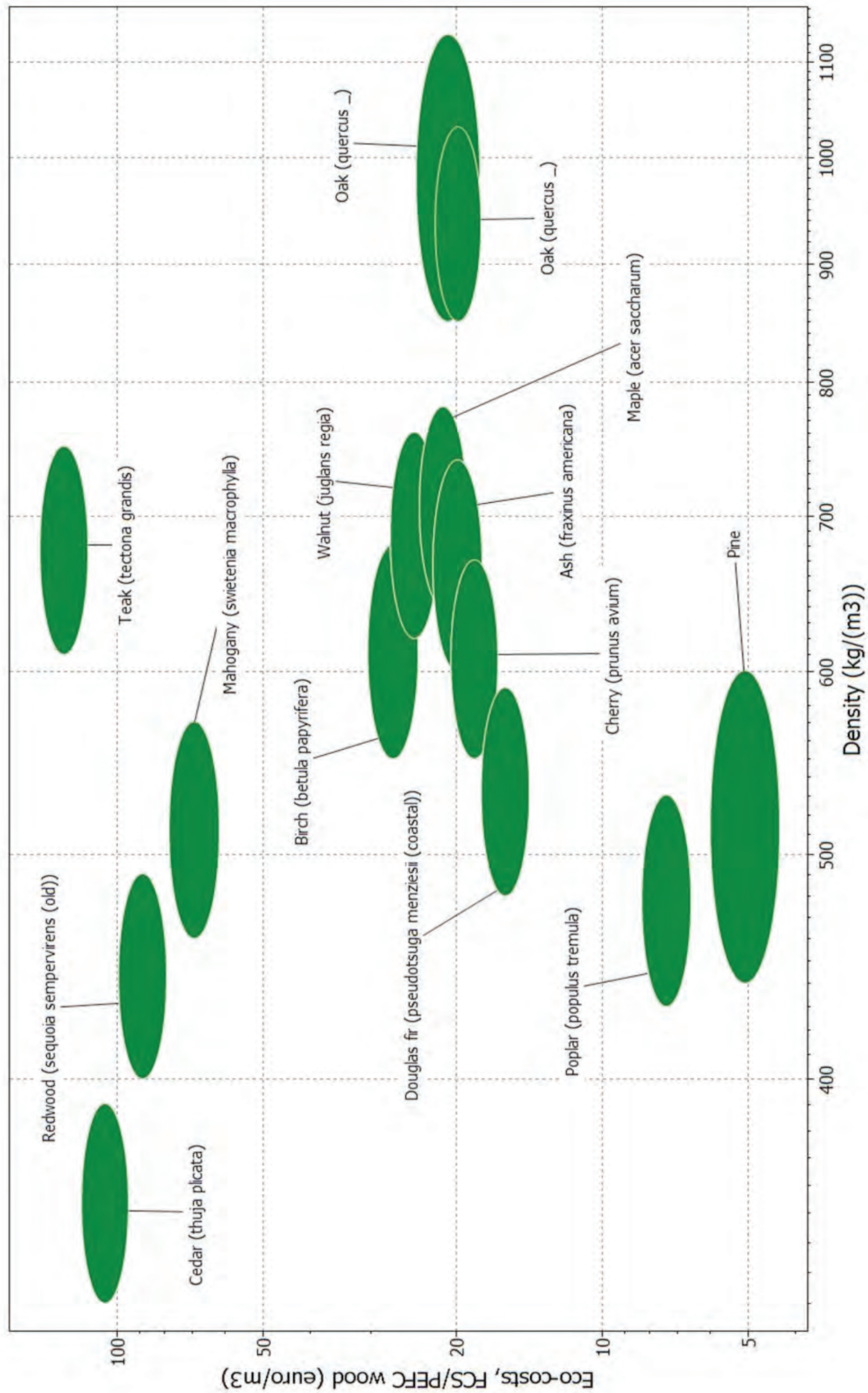

Figure 2.24 Eco-costs as a function of density for wood

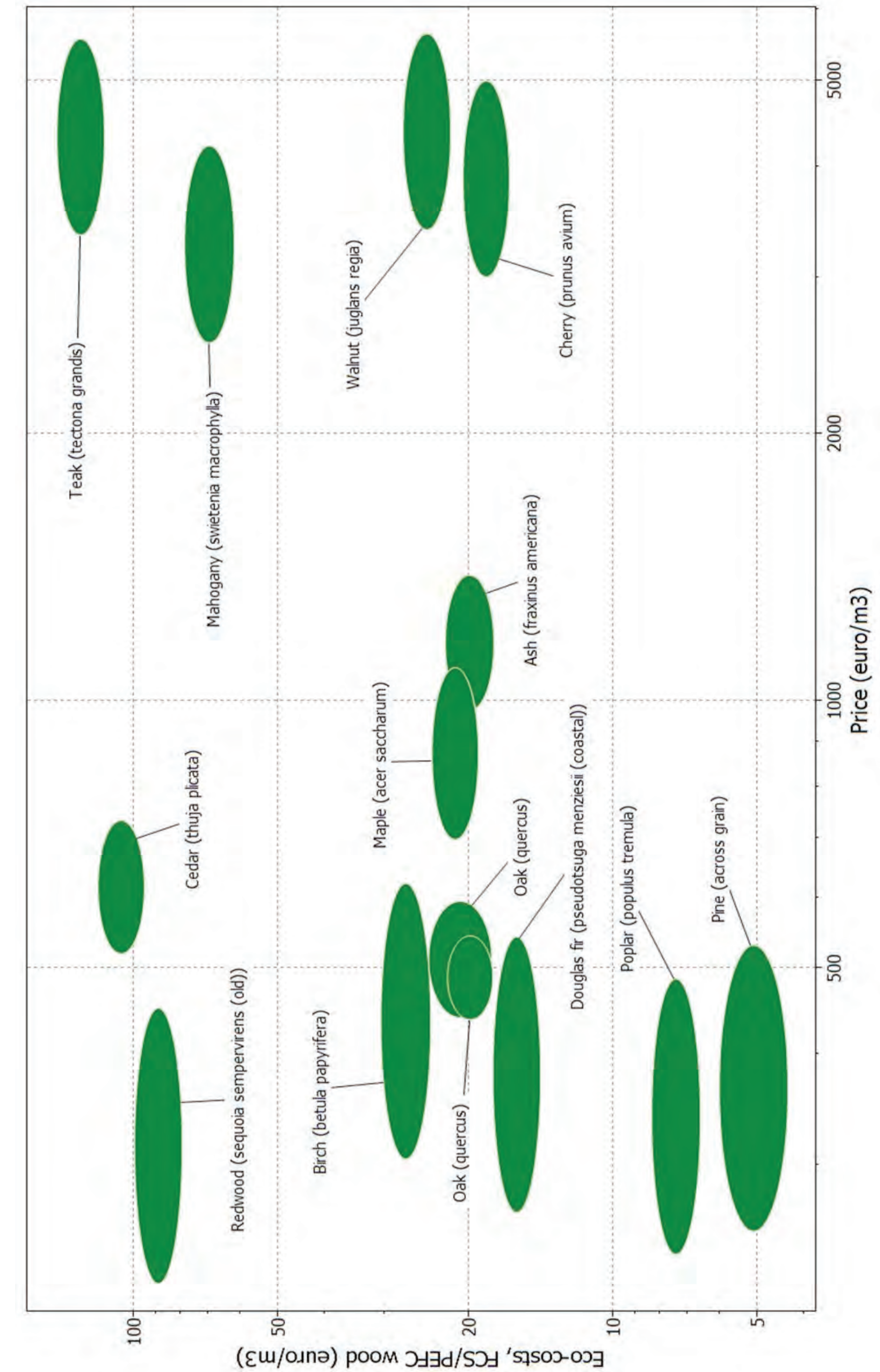

Figure 2.25 Eco-costs as a function of price for wood

Appendices

A.1 Conversion factors and prefixes

Table A.1 Conversion factors

symbol	quantity	unit	multiply by	SI-unit
L	length	inch (in)	0.0254	m
		foot (ft)	0.3048	
		yard (yd)	0.9144	
		statude mile	1609	
		nautical mile	1852	
		Ångstrom (Å)	1.E-10	
A	surface	in^2	6.45E-04	m^2
		ft^2	0.0929	
		yd^2	0.836	
		acre	4047	
		centiare (ca)	1	
		are (a)	1.E+02	
		hectare	1.E+04	
V	volume	in^3	1.64E-05	m^3
		ft^3	0.0283	
		yd^3	0.765	
		UK gallon	4.55E-03	
		US gallon	3.79E-03	
		barrel, oil	0.159	
t	time	hour	3600	s
		day	8.64E+04	
		year	3.16E+07	
m	mass	ounce (oz)	2.84E-02	kg
		once (troy)	3.11E-02	
		pound (lb)	0.454	
		ton (long)	1016	
		ton (short)	907.18	
		ton (metric)	1000	

symbol	quantity	unit	multiply by	SI-unit
F	force	poundforce (lbf)	4.45	N (kgm/s^2)
		dyn	1.E-05	
		kg force	9.81	
ρ	density	lb/in^3	2.77E+04	kg/m^3
		lb/ft^3	16.0	
p	pressure	lbf/in^2 (psi)	6.89E+03	Pa (N/m)
		kgf/cm^2 (at)	9.81E+04	
		atm (standard)	1.01E+05	
		bar	1E+05	
		mm water	9.80	
		mm Hg (torr)	1.33E+02	
Q	energy	kWh	3.60E+06	J (Ws =Nm)
		kcal	4.19E+03	
		BTU	1.06E+03	
P	power	BTU/h	0.293	W (J/s = Nm/s)
		hp (British)	746	
		hp (metric)	736	
		kcal/h	1.163	
		cal/s	4.19	
C	specific heat	kcal/kg ^oC	4.19E+03	J/kg ^oK
		BT/lb ^0F	4.19E+03	

Table A.2 S.I. Prefixes

prefix	symbol	factor
exa	E	1E+18
peta	P	1E+15
tera	T	1E+12
giga	G	1E+09
mega	M	1E+06
kilo	k	1E+03
hecto	h	1E+02
deca	da	1E+01
deci	d	1E-01
centi	c	1E-02
milli	m	1E-03
micro	μ	1E-06
nano	n	1E-09
pico	p	1E-12
femto	f	1E-15
atto	a	1E-18

A.2 LCA step by step

The LCA method has the following step by step procedure:
From: (Vogtländer, 2016, Section 3.1)

Step 1 Establish the scope and the goal of your analysis (this step might be done after step 2 in the case that it is a total new design)

- Is it a comparison of two or more products?
- Is it an attempt to improve the environmental characteristics of a typical design?
  - less, or less harmful, materials?
  - less energy in the use phase?
  - less transport?
  - better recycling or better incineration of waste for electricity?
  - cradle-to-cradle solution?
  - better durability?

Step 2 Establish the System, Functional Unit and System Boundary

- describe the function of your product or service
  - example for a coffee machine: 1000 cups of coffee per year (or: … cups over the life time)
  - example for a transport system: 50 m^3 freight over a distance of 300 km, no return payload
- make a drawing of your product system (from cradle-to-grave, or from cradle-to cradle). See the examples of Figure 2, 3 and 4.
- determine the life time of the system components
- establish one or more transport scenarios (e.g. bamboo from China or Latin America)
- establish the system boundary (what do you include and what do you neglect in your system?)

Step 3 Quantify materials, use of energy, etc. in your system

- collect (measure) data (e.g. weight, material, energy consumption)
- determine accuracy and relevance; establish allocation rules (or scenarios) and cut-off criteria

Step 4 Enter the data in an Excel calculation sheet or a computer application

- If an indicator value for a material or process is missing in the look-up table, this can be resolved as follows:
  - check whether the missing material or process could make a significant contribution to the total environmental impact, if not neglect it (if it is expected under the cut-off criterion)
  - substitute a known process for the unknown one which has the same characteristics (take a 'surrogate process'). For example: If you miss an indicator values for a certain type of plastics, find out which known plastic is similar
  - search in EPD databases (e.g. of Germany or France) and apply Appendix VI of (Vogtländer, 2016).

- take the required energy for the process, calculate the eco-burden of it, and add the eco-costs of the extreme toxic emissions and materials depletion (if any); see for the eco-costs of emissions and materials depletion www.ecocostsvalue.com, tab data.

Step 5 Interpret the results and draw your conclusions

- Once you have entered everything in your computer program or calculation sheet, you can add up the total eco-costs of your product (and/or service). However, it is not the aim of an LCA to have the total eco-costs only. The aim of LCA is always a comparison with other products and/or alternative designs or processes. So, the last step of LCA is an analysis of the total output, including relevant details.

Note: it might be that you conclude in this last step that you have to (partly) redo your calculation, since elements are missing or are not accurate enough.

A.3 Wind power

Estimation of the eco-burden of wind power in other parts of the world

In Table 1.22 the eco-burden of windpower is given:

"Electricity from offshore windmill 2 MW (Danish coast), per kWh".

- eco-costs 0.0097 (euro/kWh)
- carbon footprint 0.0166 (kg CO_2 eq/kWh)
- CED 3.96 (MJ/kWh)
- Recipe 0.0023 (Pt/kWh)

The system description is:
"Technology of a specific 2 MW offshore wind power plant, representative for average European. Includes the operation of the wind power plant with the necessary change of gear oil. Also includes the capacity factor, concerning the wind conditions: The **capacity factor is assumed to be 30 %**, based on the electricity production of the offshore wind park Middelgrunden, Denmark. Gear oil has to be changed every second year. The lifetime of moving and fixed parts is assumed to be 20 resp. 40 years.; Geography: Data for a specific European offshore conditions. Can be used for regions with similar wind conditions." (quoted from Ecoinvent v2.2)

Similar conditions can be found in Denmark, Germany, the Netehrlands, Belgium, and the UK.
The question is, however, how these Danish data relate to other (offshore) conditions in the world, outside this Noth Sea region.

The equation to calculate the eco-costs (or an other single indicator):

ecocosts (euro/kWh) = $\dfrac{\left(\frac{1}{\propto}\right) \times \left(\frac{A1}{40} + \frac{A2}{20}\right)}{B \times C}$, where:

A1 = total ecocosts of contruction and maintenance of fixed parts (euro/windmill) over the life time of 40 years
A2 = total ecocosts of contruction and maintenance of moving parts (euro/windmill) over the life time of 20 years
B = maximum operating power of the windmill (kWh)
C= hours per year = 365 × 24
α = capacity factor (note[2])= total 'equivalent' full operating hours per year / (365 × 24)

[2] The capacity factor is an utilisation factor. It is related to the availability of anough wind to operate at maximum power.

The capacity factor α depends on the location. General assumptions are: α = 0.30 for offshore windfarms, α = 0.20 for inland windfarms. When the exact location is known, α can be calculated, based on the local wind statistics, which can be found on
http://www.windguru.cz/int/historie_statsw.php?switchlang=1

The data on this website is at 10 metre above groundlevel (the international standard). Since modern windmills of 2 MW and more have the hub at 80 metres, these windvelocities must be multiplied bij a factor 1.3.

Global maps for 80 m (as well as 10 m) are given at
http://www.stanford.edu/group/efmh/winds/global_winds.html
Figure A.4 and A.5 give the map of Europe and North America (for other regions of the world, see the website).
In practice, the offshore windfarms are located in areas of windclass 6 and 7, with an annual average windspeed more than 8.6 m/s (5 Beaufort), leading to a capacity factor α of 0.30.
Since inland windfarms requires smaller investments, inland windfarms are built in areas of windclass 3 and more, with an annual average windspeed of more than 6.9 m/s (4 Beaufort), and capacity factors α of approximately 0.20. Note that the Swiss examples in the Ecoinvent database have lower capacity factors, which corresponds with the fact that Switzerland scores lower than windclass 3 on the map of Figure A.4.

Another issue is the size of the windmill in the case of an inland location. Under the assumption that the capacity factor is 0.20, the eco-costs (euro/kWh) have been calculated for the 4 windmills which are available in the Ecoinvent database. See Figure A.1 for eco-costs, 'normalised' at a capacity factor of 0.20.

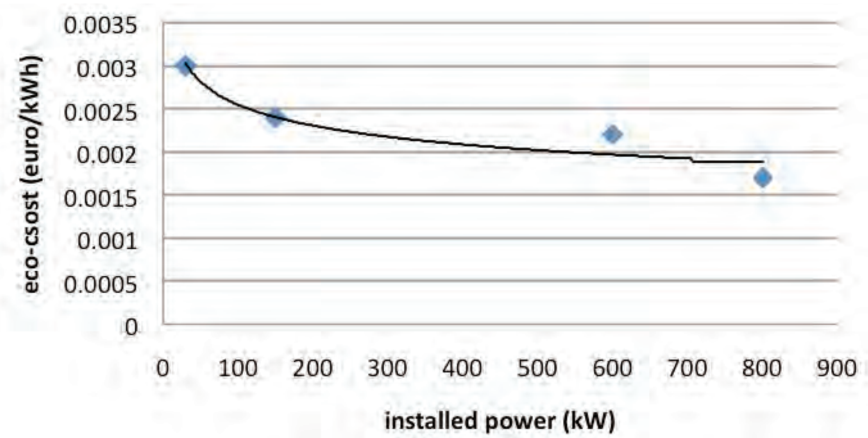

Figure A.1 Normalised eco-costs of inland windmills

Additional information on the calculation of the capacity factor

The calculation of the capacity factor α of a windmill is quite complex·. See:

- http://www.engineeringtoolbox.com/wind-power-d_1214.html

- http://www.mpoweruk.com/wind_power.htm

The basics of the calculation are explained with the help of Figure A.2 and A.3 (from the first website, the second website explains the basics of the calculation in a bit more depth).

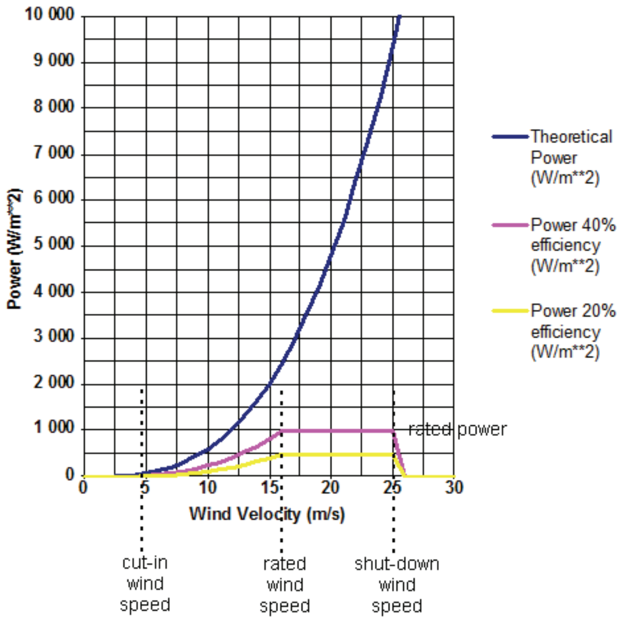

Figure A.2 Power (P) as a function of wind velocity (m/s) - www.engineeringtoolbox.com

The black curve gives the power **P** available in the wind impinging on a windturbine and can be expressed as:

$$\mathbf{P} = \frac{1}{2}\ \mathbf{CA}\rho v^{3}$$

where **C** is an efficiency factor known as the Power Coefficient which depends on the machine design, **A** is the area of the wind front intercepted by the rotor blades (the swept area), ρ is the density of the air (averaging 1.225 kg/m³ at sea level) and v is the wind velocity.
The yellow and purple lines in Figure A.2 indicate the part of the wind power that is captured by the windmill, being the "wind speed-power curve". The cut-in wind speed is the wind velocity at which operation can start. The rated wind speed is the design wind velocity of the windmill. For wind velocities above the design velocity, the the pitch of the blades is turned to reduce the force on the blades. At the shut-down wind speed, operation is stopped for safety reasons. The first part of the wind speed power curve shows the efficiency of the rotor blades, which is normally between 40% (the purple curve) and 20% (the yellow curve).

The energy generated by a windmill depends on the power generation as indicated above, and the "wind speed frequency distribution" at the actual location as given below. The total energy generated over a year can be calculated by summarizing the power generation for all velocities (ranging from the actual windmill cut-in speed to the shut-down speed) multiplied with the number of hours the wind blows at the actual speeds. See Figure A.3.

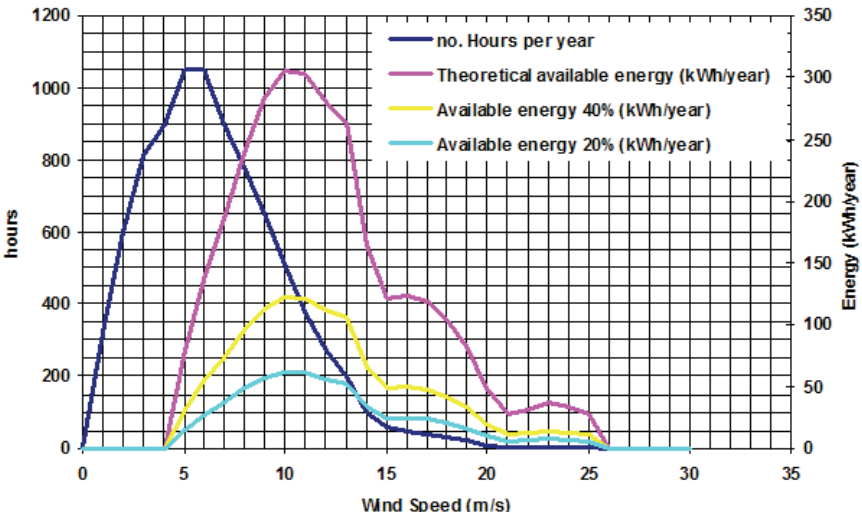

Figure A.3 Total energy (KWh/year) as a function of wind speed (m/s) - www.engineeringtoolbox.com

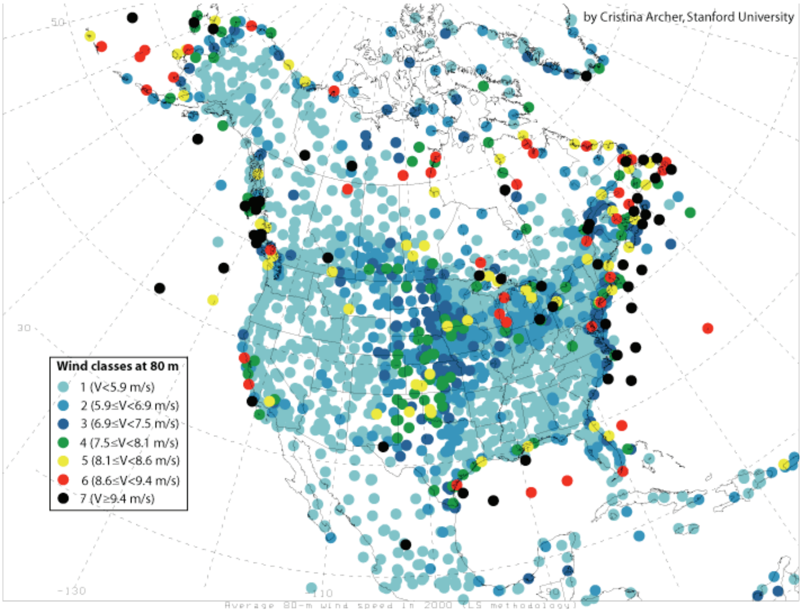

Figure A.4 Different wind classes at 80 m for North America

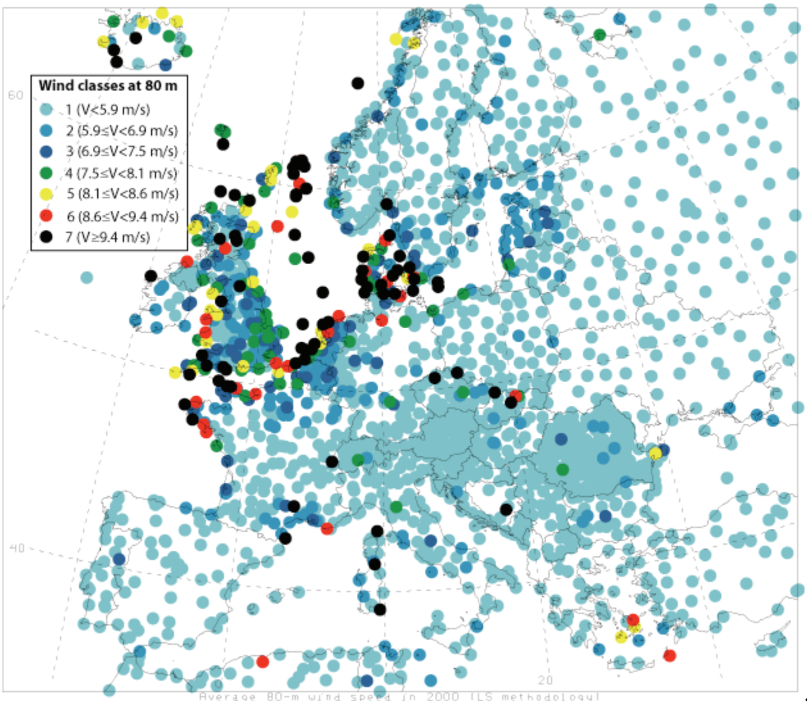

Figure A.5 Different wind classes at 80 m for Europe

A.4 Solar power

Calculation of the eco-burden of solar power in other parts of the world

In Table 1.22 the eco-burden of solar power of a PV cell is given for
"PV panel on the roof 3 kWp, ribbon-Si, Switserland, per kWh":

- eco-costs 0.0256 (euro/kWh)
- carbon footprint 0.0756 (kg CO_2 eq/kWh)
- CED 5.04 (MJ/kWh)
- Recipe 0.0089 (Pt/kWh)

The system description is:
"Electricity production with grid-connected photovoltaic power plants mounted on buildings with a slanted roof. Infrastructure for 3kWp PV-plant[3]. Water use for cleaning. Amount of solar energy transformed to electricity. Waste heat emission due to losses of electricity in the system. Assumption for electricity production of photovoltaic plants with good performance. Average performance is lower while optimum performance would be higher. Total capacity in Switzerland for the year 2005 was 23.8 MWp. Dataset can be used for comparison of energy technologies in Switzerland, but not for assessment of average production patterns. Yield data must be corrected for the installations used in other countries." (quoted from Ecoinvent v2.2).

Further documentation shows that the panel surface area is 25,75 m^2 and has a cell efficiency of 12% (conversion of solar radiation energy to electrical power at 25 °C), and the Performance Ratio (efficiency reduction by radiation losses, temperature losses and inverter efficiency) to the grid is 75%.

The question is, however, how these Swiss data relate to data in other areas of the world.

The key to translation of the Swiss data to other areas are maps on solar irradiation (also called insolation). There are 3 types of maps:

- maps on the irradiation on the flat horizontal surface
- maps on the irradiation on a (fixed) tilted panel
- maps on 'peak sun hours' (often presented for the worst month of the year), often for fixed tilted panels

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[3] The unit kWp (=kWpeak) relates to a 'peak sun hour'. A peak sun hour is the equivalent number of hours per day for a solar irradiance of 1000 W/m^2. In other words, a peak sun hour is defined as 1 kWh/m^2 irradiance per hour. It can be used to express the irradiation per day. So 3 peak sun hours equal to an irradiation of 3 kWh/m^2 per day.
The peak sun hour is also used to define the performance of a PV system. A PV system of 1 kWp delivers 1 kWh in 1 sun peak hour. Note that a PV panel of 1 kWp has a surface area of 1/[cell efficiency]. Cell efficiencies of current systems on the market are 12 – 15%, resulting in surface areas of 8.3 – 6.6 m^2 per kWp. For developments of cell efficiencies see http://en.wikipedia.org/wiki/Solar_cell

In this section, a map on the irradiation of tilted panels in Europe is taken as an example on how to convert the Swiss data to other places on the world. The European map is given in Figure A.6. When we assume that the Swiss panels are located in the middele of Switserland (near the city of Bern), the irradiation is approximately 1350 kWh/m^2 per year.

The first orde approximation of the eco-costs (in euro/kWh) at any other location on earth is eco-costs of electricity from PV panels (euro/kWh)

$$= 0.0256 \times \frac{1350}{\text{annual local irradiation}}$$

in which the annual local radiation is expressed in kWh/m^2
The same applies to the carbon Footprint, the CED and Recipe Points.

There are detailed maps of irradiation on tilted panels for each country within the EU, see http://re.jrc.ec.europa.eu/pvgis/cmaps/eur.htm .
The annual irradiation in The Netherlands ranges from 1200 (kWh/m^2) in the North – West of the country to 1100 (kWh/m^2) in the South – East.

Deatiled horizontal irradiation maps for Africa are available as well on the EU website http://re.jrc.ec.europa.eu/pvgis/cmaps/afr.htm
A good overview of all countries around the globe is given for horizontal irradiation http://www.helpsavetheclimate.com/solar.html

Additional information

It is outside the scope of this guide to provide information on how to make calculations on the performance of PV cells, however, some URLs are given for people who want to know more about it.
For Dutch people there is a practical website on PV panels and what you can expect in terms of electrical output (efficiency) and costs:
http://www.siderea.nl/zonne-energie/faq/faq.html
In the English language, the information is more scattered. Some websites:
http://www.pveducation.org/pvcdrom/instructions
http://solarcellcentral.com/index.html
http://www.ashdenawards.org/solar-grid
http://www.fsec.ucf.edu/en/research/photovoltaics/data_monitoring/use_interp_data.htm
Developments of the cell efficiency (current PV cell on the market, and developments in laboratories) are given at Wikipedia http://en.wikipedia.org/wiki/Solar_cell

The best overall Performance Ratio (efficiency of the PV panel system) is reached by connecting the PV cell to the power grid (efficiencies 75 – 85 %). Stand alone systems with battery packs have a much lower efficiency (in practice approximately 10% extra losses for LiIon batteries and 20% extra losses for Lead batteries) because of losses in loading, storage and unloading of the batteries.

For stand alone applications the worst period is important. Global maps on the worst month (averages on peak sun hours) are given at:
http://www.pveducation.org/pvcdrom/properties-of-sunlight/average-solar-radiation
Note that a cloudy day (total overcast sky) can result in less than 10% output of a bright sunny day.
Variations of the irradiation in the US are provided per month (average, minimum, maximum) and distinguishing in collector orientation, see the maps at:
http://www.ametsoc.org/amsedu/proj_atm/modules/Sun&Seasons.pdf

The photovoltaic Solar Power Potential in Europe, as given in Figure A.6 is from:
http://re.jrc.ec.europa.eu/pvgis/cmaps/eur.htm .

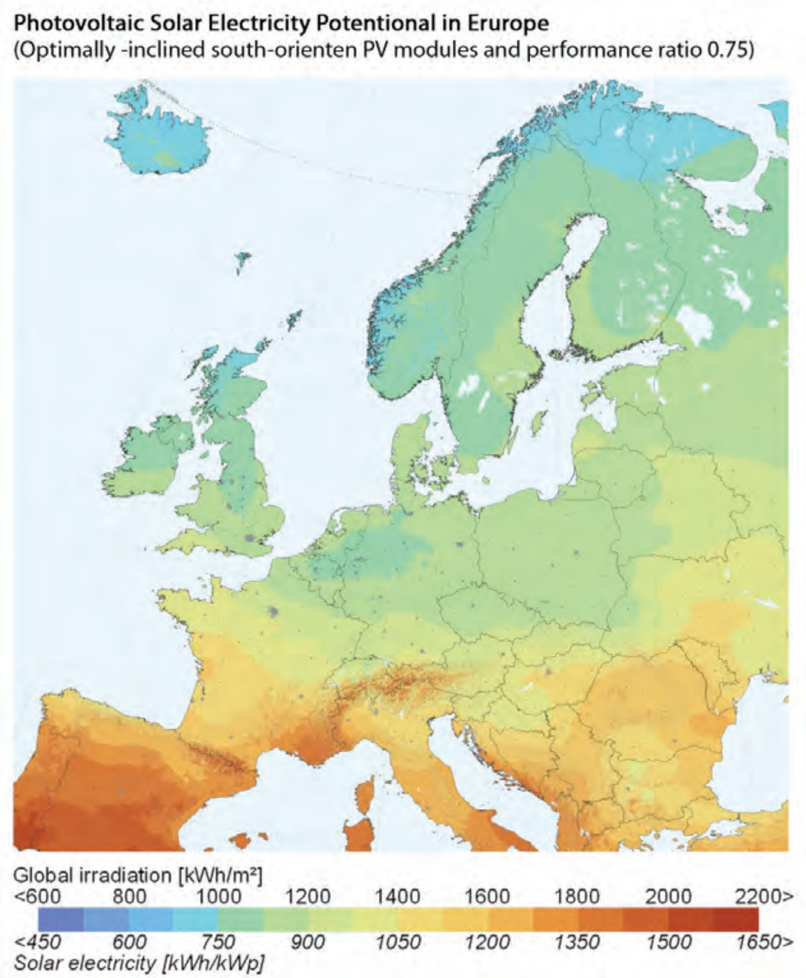


Figure A.6 Photovoltaic Solar electricity potentional in europe - Reference: Šúri M., Huld T.A., Dunlop E.D. Ossenbrink H.A., 2007. Potential of solar electricity generation in the European Union member states and candidate countries. Solar Energy, 81, 1295–1305, http://re.jrc.ec.europa.eu/pvgis/.

A.5 Recycling credits of coloured polymers

The recycling credits of polymers in Section 1.6 are for the case of uncoloured materials. In (Vogtländer, 2010), page 52, a simple formula is proposed to estimate the credits of coloured plastics on the basis of economic allocation:

$$\text{credit of coloured materials} = A \times \frac{B}{C}$$

where:
A = credit of uncoloured material
B = price of coloured material
C = price of uncoloured material

The market price of coloured PET bottles to be recycled is approximately 60% of the price of uncoloured bottles. The market price of coloured HDPE bottles is about 69% of the price of uncoloured bottles

This results in the data for eco-costs and the other single indicators in Table A.3.

Table A.3 Recycling credits of polymers

polymers (per kg) recycling credits Idemat 2010	eco- costs euro	carbon footprint kg CO_2 eq	CED MJ	recipe Pt
PET, uncoloured, recycling credit	–0.76	–0.84	–30.6	–0.174
PET, coloured, recycling credit	–0.46	–0.50	–18.4	–0.104
PE, uncoloured, recycling credit	–0.46	no credit	–10.9	–0.012
PE, coloured, recycling credit	–0.32	no credit	–7.52	–0.008

For other types of plasics, the price ratio is not known. It seems that 60% reduction of the credits is a realistic guess, for most plastics. However, a much more accurate approach to calculate the recycling credits of plastics is given at (Vogtlander et al., 2014) in Appendix IX. This approach is is fully in line with the formal LCA requirements, but is a bit more complex than the above formula..

Additional information

Although it is outside the scope of this guide to provide information on the design of plastic bottles, some information is given below, especially on the issue of mixed types of polymers and on the issue of pigments and ink. This information is from the document "Plastics Packaging, Recyclability by Design" published by Recoup, UK. See
http://www.recoup.org/p/173/download-centre

"In an ideal world, use of mono-materials or mixed materials of the same type are the preferred choice from a recycler's point of view. In this context, type means materials that for all intents and purposes act as if they were a homogeneous material i.e. they are fully compatible, do not downgrade the properties of the recycled plastic and can be sorted and subsequently processed as if it were a single material."

It is recognised that to provide both the technical properties required and to satisfy user needs, sometimes a combination of different types of material is required. Under these circumstances, materials of different densities should be used to facilitate the separation of incompatible materials during mechanical shredding or crushing, or during the subsequent water-based washing process. Combinations of different types of plastic with the same density ranges should be avoided.

Fillers that change the density of the plastic should be avoided and/or their use minimised in general as they lower the quality of the recycled material.

Unpigmented polymer has the highest recycling value and the widest variety of end uses. For food contact applications, the additional specific requirements of traceability, guarantee of the use of qualified processes and producer responsibility for recyclates would ensure that specifiers use only food-approved additives to maintain the potential for the recyclate to be subsequently used in food applications."

"Colour interferes with the mechanical recycling process in two main ways: Firstly, strongly coloured plastic material has a much lower economic value than nonpigmented plastic. Secondly, heavily coloured (and hence strongly light absorbing) plastic may interfere with automated sorting machinery that uses NIR spectroscopy to identify the nature of the plastic. Such equipment relies on the reflection of NIR radiation and thus there is an issue in identifying carbon black plastic items. The amount of colour to be used should be minimised as much as possible.

Where use of colour is necessary, designers are encouraged to consider alternative approaches (e.g. sleeves) that will further facilitate recyclability.

Avoid direct printing onto natural (not coloured or opacified) plastics."

"Inks and pigments selected to colour and print the container and label already have to comply with existing restrictions on the use of heavy metal components and, although beyond the scope of these guidelines, also with relevant health and safety regulations. In any case, hazardous substances should be avoided in the interests of good manufacturing practice and heavy metal inks not used for printing as they may contaminate the recovered plastic. For these reasons, it is recommended that the regularly updated exclusion list for printing inks and related products, provided by the European Printing Ink Association (EuPIA) is followed. Inks that would dye the wash solution should be avoided as this may discolour the recovered plastic diminishing or eliminating its value. APR, NAPCOR and The European PET Bottle Platform have testing protocols to assist label manufacturers to assess whether a label ink will bleed in a conventional PET recycling process. Heavily pigmented containers should be avoided. They can result in a significant increase in the density of the polymer thereby causing separation problems and can also cause problems for automated sorting equipment using NIR sensors."

For further advice on the design of plastic bottles (e.g. the choice of the material of closures, the choice of sleeves, lables, adhesives, the application of RFIDs, etc.) can be found in the aforementioned document and the Recoup website www.recoup.org.

A.6 Determination of polymers

Students often struggle with the question: "which type of plastics is this?". The type of plastics is often indicated somewere at the bottle or the plactic component of the product. See Table A.4, source http://en.wikipedia.org/wiki/Resin_identification_code

Table A.4 Determination of polymers

Image	Unicode	Abbreviation	Polymer name	Uses
♳	U+2673	**PETE or PET**	Polyethylene terephthalate	Polyester fibres, thermoformed sheet, strapping, and soft drink bottles
♴	U+2674	**HDPE**	High density polyethylene	Bottles, grocery bags, milk jugs, recycling bins, agricultural pipe, base cups, car stops, playground equipment, and plastic lumber
♵	U+2675	**PVC or V**	Polyvinyl chloride	Pipe, fencing, and non-food bottles
♶	U+2676	**LDPE**	Low density polyethylene	Plastic bags, 6 pack rings, various containers, dispensing bottles, wash bottles, tubing, and various molded laboratory equipment
♷	U+2677	**PP**	Polypropylene	Auto parts, industrial fibers, food containers, and dishware
♸	U+2678	**PS**	Polystyrene	Desk accessories, cafeteria trays, plastic utensils, toys, video cassettes and cases, and insulation board and other expanded polystyrene products (e.g., Styrofoam)
♹	U+2679	**OTHER or O**	Other plastics, including acrylic, acrylonitrile butadiene styrene, fiberglass, nylon, polycarbonate, and polylactic acid	Bottles, plastic lumber applications, Headlight lenses, and safety shields/glasses

If the material has no code, identification is less simple. Students can find more information in CES EduPack and CES Selector. A relative simple identification method is to check the density (first question: does it float or not?). See Table A.5.

Table A.5 Desity of polymers

Polymer	Density g/cm^3	Behaviour in water
Ethylene vinyl acetate (EVA)	Less dense than water	float
Polypropylene (PP)	0.90 – 0.92	float
Low density polyethylene (LDPE)	0.91 – 0.93	float
High density polyethylene (HDPE)	0.94 – 0.96	float
Polystyrene (PS)	1.03 – 1.06	variable
Nylon (PA)	1.13 – 1.14	sink
Acrylic (PMMA)	1.17 – 1.20	sink
Polycarbonate (PC)	1.19 – 1.21	sink
Polyethylene terephthalate (PET)	1.30-1.38	sink
Polyvinyl chloride (PVC)	1.32-1.45	sink

A.7 Eco-costs 2012

From Wikipedia.

General

Eco-costs are a measure to express the amount of environmental burden of a product on the basis of prevention of that burden. They are the costs which should be made to reduce the environmental pollution and materials depletion in our world to a level which is in line with the carrying capacity of our earth.

For example: for each 1000 kg CO_2 emission, one should invest € 135,- in offshore windmill parks (and the other CO_2 reduction systems at that price or less). When this is done consequently, the total CO_2 emissions in the world will be reduced by 65% compared to the emissions in 2008. As a result global warming will stabilise. In short: "the eco-costs of 1000kg CO_2 are € 135,-".

Similar calculations can be made on the environmental burden of acidification, eutrification, summer smog, fine dust, eco-toxicity, and the use of metals, rare earth, fossil fuels and land (nature). As such, the eco-costs are virtual costs, since they are not yet integrated in the real life costs of current production chains (Life Cycle Costs). The eco-costs should be regarded as hidden obligations.

The eco-costs of a product are the sum of all eco-costs of emissions and use of materials and energy during the life cycle "from cradle to cradle". The widely accepted method to make such a calculation is called Life Cycle Assessment (LCA), which is basically a mass and energy balance, defined in the 14040 and ISO 14044.

The practical use of eco-costs is to compare the sustainability of several product types with the same functionality. The advantage of eco-costs is that they are expressed in a standardized monetary value (€) which appears to be easily understood 'by instinct'. Also the calculation is transparent and relatively easy, compared to damage based models which have the disadvantage of extremely complex calculations with subjective weighting of the various aspects contributing to the overall environmental burden.

The system of eco-costs is part of the bigger model of the EVR (see Appendix IV).

Background

The eco-costs system has been introduced in 1999 on conferences, and published in 2000-2004 in the International Journal of LCA, and in the Journal of Cleaner Production. In 2007 the system has been updated, and published in 2010. It is planned to update the system every 5 years to incorporate the latest developments in science. In the summer of 2012 a new update has been released.

The concept of eco-costs has been made operational with general databases, and is described at www.ecocostsvalue.com of the Delft University of Technology.
The method of the eco-costs is based on the sum of the marginal prevention costs (end of pipe as well as system integrated) for toxic emissions related to human health as well as ecosystems,

emissions that cause global warming, and resource depletion (metals, rare earth, fossil fuels, water, and land-use). For a visual display of the system see Fig. A.7.

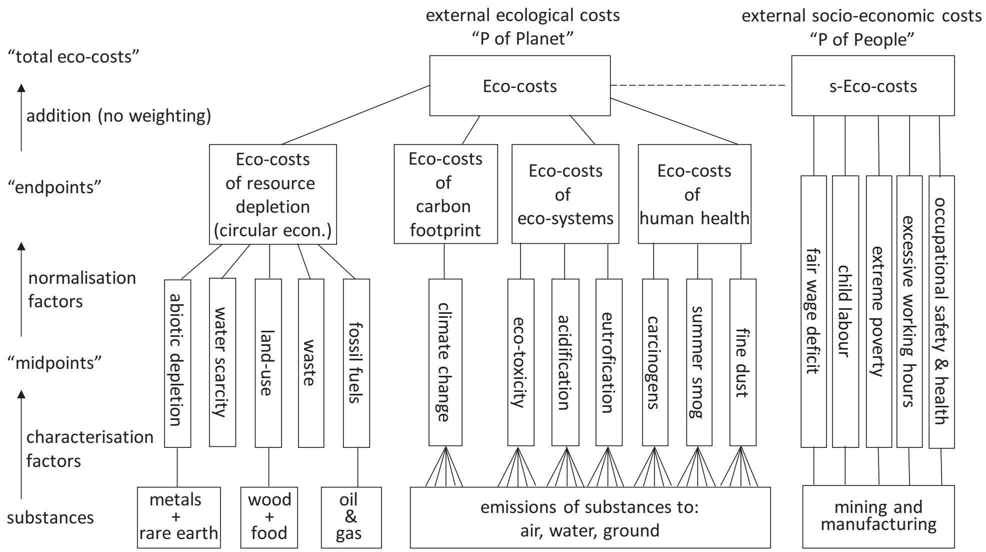


Figure A.7 The eco-costs 2012 calculation structure

Marginal prevention costs of toxic emissions are derived from the so called prevention curve as depicted in Fig. A.8. The basic idea behind such a curve is that a country (or a group of countries, such as the European Union), must take prevention measures to reduce toxic emissions (more than one measure is required to reach the target).

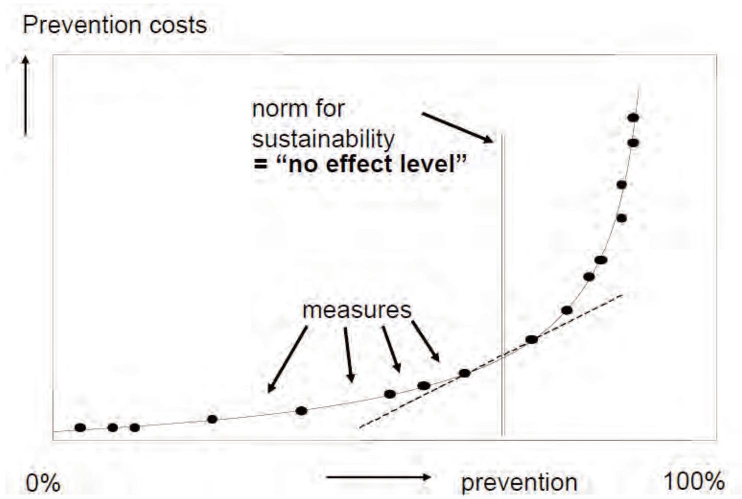


Figure A.8 The prevention curve and the marginal prevention costs

From the point of view of the economy, the cheapest measures (in terms of euro/kg) in Fig. A.8 are taken first. At a certain point at the curve, the reduction of the emissions is sufficient to bring the concentration of the pollution below the so called no-effect-level. The no-effect-level of CO2 emissions is the level that the emissions and the natural absorption of the earth are in equilibrium again at a maximum temperature rise of 2 degrees C. The no-effect-level of toxic emission is the level where the concentration in nature is below the toxicity threshold (most natural toxic substances have a toxicity threshold, below which they might even have a beneficial effect), or below the background level. This is also called the 'no observable adverse effect level'.
The eco-costs are the marginal prevention costs of the last measure of the prevention curve to reach the no-effect-level. A full description of the calculation method in the aforementioned journals (note that in the calculation 'classes' of emissions with the same 'midpoint' are combined, as explained below).

The classical way to calculate a 'single indicator' in LCA is based on the damage of the emissions. Pollutants are grouped in 'classes', multiplied by a 'characterisation' factor to account for their relative importance within a class, and totalised to the level of their 'midpoint' effect (global warming, acidification, nutrification, etc.). The classical problem is then to determine the relative importance of each midpoint effect. This is done by 'normalisation' (= comparison with the pollution in a country or a region) and 'weighting' (= giving each midpoint a weight, to take the relative importance into account) by an expert panel.

The calculation of the eco-costs is based on classification and characterisation tables as well (combining tables from IPCC, the UseTox model, tables of ReCiPe, the ILCD, and RiskPoll); however, the method has a different approach to the normalisation and weighting steps. Normalisation is done by calculating the marginal prevention costs for a region (i.e. the European Union), as described above. The weighting step is not required in the eco-costs system, since the total result is the sum of the eco-costs of all midpoints. The advantage of such a calculation is that the marginal prevention costs are related to the cost of the most expensive Best Available Technology which is needed to meet the target, and the corresponding level of Tradable Emission Rights which is required in future. Example: For reduction of CO_2 emissions to a sustainable level, the marginal prevention costs are the costs of replacement of coal-fired power plants by windmill parks at the sea.

The eco-costs have been calculated for the situation in the European Union. It might be argued that the eco-costs are also an indication of the marginal prevention costs for other parts of the globe, under the condition of a level playing field for production companies.

Eco-costs 2012

The method of the eco-costs 2012 (version 2.00 and 3.00) comprises tables of over 3000 emissions, and has been made operational by special database for Simapro, based on LCIs from Ecoinvent V3, Idemat 2015, and Agri Footprint, (over 10.000 materials and processes), and a database for CES (Cambridge Engineering Selector). Excel look-up tables are provided at www.ecocostsvalue.com.

For emissions of toxic substances, the following set of multipliers is used in the eco-costs 2012 system:

- prevention of acidification 8.25 €/kg SOx equivalent
- prevention of eutrophication 3.90 €/kg phosphate equivalent
- prevention of ecotoxicity 55 €/kg Zn equivalent
- prevention of carcinogens 36 €/kg Benzo(a)pyrene equivalent
- prevention of summer smog (respiratory diseases) 9.70 €/kg C2H4 equivalent
- prevention of fine dust 34 €/kg fine dust PM2.5
- prevention of global warming (GWP 100) 0.135 €/kg CO_2 equivalent

The characterisation ('midpoint') tables which are applied in the eco-costs 2012 system are recommended by the ILCD (and brought in line with EN15804):

- IPPC 2013, 100 years, for greenhouse gasses
- USETOX, for human toxicity (carcinogens), and ecotoxicity
- RECIPE, for eutrification, and photochemical oxidant formation (summer smog)
- ILCD, for acidification
- RiskPoll, for fine dust

In addition to abovementioned eco-costs for emissions, there is a set of eco-costs to characterize the 'midpoints' of resource depletion:

- eco-costs of abiotic depletion (metals, including rare earth, and fossil fuels)
- eco-costs of land-use change (based on loss of biodiversity, e.g. used for eco-costs of tropical hardwood)
- eco-costs of water (based on the midpoint Water Stress Indicator - WSI - of countries)
- eco-costs of landfill

The abovementioned marginal prevention costs at midpoint level can be combined to 'endpoints' in three groups, plus global warming as a separate group:

eco-costs of human health	= the sum of carcinogens, summer smog, fine dust
eco-costs of ecosystems	= the sum of acidification, eutrophication, ecotoxicity
eco-costs of resource depletion	= the sum of abiotic depletion, land-use, water, and land-fill
eco-costs of global warming	= the sum of CO2 and other greenhouse gases (the GWP 100 table)
total eco-costs	= the sum of human health, ecosystems, resource depletion and global warming

Since the endpoints have the same monetary unit (e.g. euro, dollar), they are added up to the total eco-costs without applying a 'subjective' weighting system. This is an advantage of the eco-costs system (see also ISO 14044 section 4.4.3.4 and 4.4.5). So called 'double counting' (ISO 14044 section 4.4.2.2.3) is avoided in the eco-costs system.

The eco-costs of global warming (also called eco-costs of carbon footprint) can be used as an indicator for the *carbon footprint*. The eco-costs of resource depletion can be regarded as an indicator for 'circularity' in the theory of the *circular economy*. However, it is advised to include human toxicity and eco-toxicity, and include the eco-costs of global warming in the calculations on the circular economy as well. The eco-costs of global warming are required to reveal the difference between fossil-based products and bio-based products, since biogenic CO_2 is not counted in LCA (biogenic CO_2 is part of the natural recycle loop in the biosphere). Therefore, total eco-costs can be regarded as a robust indicator for *cradle-to-cradle* calculations in LCA for products and services in the theory of the circular economy. Since the economic viability of a business model is also an important aspect of the circular economy, the added value of a product-service system should be part of the analysis. This requires the two dimensional approach of Eco-efficient Value Creation [9], see Appendix IV.

The Delft University of Technology is working on a Version 3.00 of the eco-costs 2012. In this version, metrics on **social aspects** of the production chain have been added. Aspects are the low minimum wages in developing countries (the 'wage deficit'), the aspects of 'child labour' and 'extreme poverty', the aspect of 'excessive working hours', and the aspect of 'OSH (Occupational Safety and Health)'.

Prevention costs versus damage costs

Prevention measures will decrease the costs of the damage, related to environmental pollution (e.g. damage costs related to human health problems in terms of DALYs). The savings which are a result of the prevention measures are of the same order of magnitude as the costs of prevention. So the total effect of prevention measures on our society is that it results in a better environment at virtually no extra costs, since costs of prevention and costs of savings will level out.

Discussion

There are many "single indicators" for LCA. Basically they fall in three categories:

- single issue
- damage based
- prevention based

The best known 'single issue' indicator is the carbon footprint: the total emissions of kg CO_2, or kg CO_2 *equivalent* (taking methane and some other greenhouse gasses into account as well). The advantage of a single issue indicator is, that its calculation is simple and transparent, without any complex assumptions. It is easy as well to communicate to the public. The disadvantage is that is ignores the problems caused by other pollutants and it is not suitable for cradle to cradle calculations (because resource depletion is not taken into account).

The most common single indicators are damage based. This stems from the period of the 1990s, when LCA was developed to make people aware of the damage of production and consumption. The advantage of damage based single indicators is, that they make people aware of the fact that they should consume less, and make companies aware that they should produce cleaner. The disadvantage is that these damage based systems are very complex, not transparent for others than who make the computer calculations, need many assumptions, and suffer from the subjective weighting procedure at the end. Communication of the result is not easy, since the result is expressed in 'points' (attempts to express the results in money were never very successful, because of methodological flaws and uncertainties).

Prevention based indicators, like the system of the eco-costs, are relatively new. The advantage, in comparison to the damage based systems, is that the calculations are relatively easy and transparent, and that the results can be explained in terms of money and in measures to be taken. The system is focused on the decision taking processes of architects, business people, designers and engineers. The disadvantage is that the system is not focused on the fact that people should consume less.

The eco-costs method is not the only prevention based indicator system. The eco-costs are calculated for the situation of the European Union, but are applicable worldwide under the assumption of a level playing field for business, and under the precautionary principle. There are two other prevention based systems, developed after the introduction of the eco-costs, which are based on the local circumstances of a specific country:

- In the Netherlands, 'shadow prices' have been developed in 2004 by TNO/MEP on basis of a local prevention curve: it are the costs of the most expensive prevention measure required by the Dutch government for each midpoint. It is obvious that such costs are relevant for the local companies, but such a shadow price system doesn't have any meaning outside the Netherlands, since it is not based on the no-effect-level
- In Japan, a group of universities have developed a set of data for maximum abatement costs (MAC, similar to the midpoint multipliers of the eco-costs as given in the previous section), for the Japanese conditions. The development of the MAC method started in 2002 and has been published in 2005. The so-called avoidable abatement cost (AAC) in this method is comparable to the eco-costs.

Reference: (Vogtländer, et al., 2014) (Vogtländer et al., 2010)

A.8 Statics

Although it is outside the scope of this guide to give details on calculations on the statics of structures, it might be necessary to estimate the size of a beam in the early design phase, in order to know the quantity of the material in the beam (this issue is related to the issue of materials selection in the charts of Chapter 2).

List of symbols:

b = width, internal
B = width, external
δ = deflection, displacement
d = diameter, inside
D = diameter, outside
E = modulus of elasticy, Youngs modulus
F = force
F_{cr} = critical force (maximum force before collapse or permanent deformation)
h = height, internal
H = height, external
I = moment of inertia (second moment), see Table A.8
L = length
M_{cr} = critical bending moment (maximum bending moment before collapse)
q = distributed load (force per unit distance)
q_{cr} = critical distributed load (maximum force per unit distance)
σ_{max} = yield strength (elastic limit, at 0.2% permanent deformation)
R_m = tensile strength (when yield strength is not known take $\sigma_{max} = 0.7\ R_m$)
W = section modulus, see Table A.8

The equations to calculate the deflection and the critical load are given in Table A.6.
The equations to calculate the critical load for buckling are given in Table A.7.
Equations for more cases can be found at http://engineersedge.com/beam-deflection-menu.htm

The formulas in Tables A.6 and A.7 contain the second moment of inertia, I, and the section modulus, W. These variables are a function of the cross section, see Table A.8.
The properties of universal beam shapes (I-beam, IPE-beam, H-beam, HE-beam L-beam, UNP-beam, etc.) can be found on internet. An interesting shape is a castellated beam (Dutch: raatligger) or cellular beam, since it combines high strength with low weight, see for IPE and HE data
http://www.grunbauer.nl/eng/lijst2.htm#ipe
Note: $M_{cr} = W\sigma_{max}$, with $W = I/e$, where e is the maximum distance between the neutral line and the outside of the beam (for symmetric beams: $H/2$).

Table A.6 Deflection and critical load of a beam

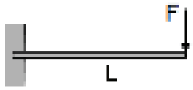
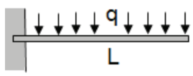
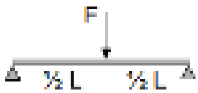
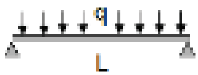
case	deflection	critical load
	$\delta = \frac{FL^3}{3EI}$	$F_{cr} = \frac{\sigma_{max} W}{L}$
	$\delta = \frac{qL^4}{8EI}$	$q_{cr} = \frac{2\sigma_{max} W}{L^2}$
	$\delta = \frac{FL^3}{48EI}$	$F_{cr} = \frac{4\sigma_{max} W}{L}$
	$\delta = \frac{5qL^4}{384EI}$	$q_{cr} = \frac{8\sigma_{max} W}{L^2}$

Table A.7 The critical load for buckling of a beam

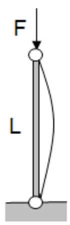
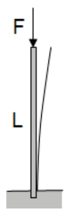
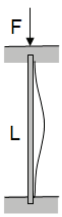
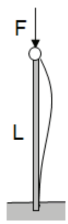
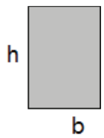
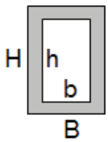
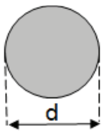
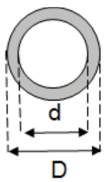
case	critical load	case	critical load
	$F_{cr} = \frac{\pi^2 EI}{L^2}$		$F_{cr} = \frac{\pi^2 EI}{4L^2}$
	$F_{cr} = \frac{4\pi^2 EI}{L^2}$		$F_{cr} = \frac{2.046\pi^2 EI}{L^2}$

Table A.8 The second moment of inertia, I, and the section modulus, W.

shape	second moment of inertia	section modulus
	$I = \frac{1}{12} bh^3$	$W = \frac{1}{6} bh^2$
	$I = \frac{1}{12}(BH^3 - bh^3)$	$W = \frac{(BH^3 - bh^3)}{6H}$
	$I = \frac{\pi}{64} d^4$	$W = \frac{\pi}{32} d^3$
	$I = \frac{\pi}{64}(D^4 - d^4)$	$W = \frac{\pi(D^4 - d^4)}{32D}$

On the following pages the Youngs modulus, E, is given for polymers as function of the ambient temperature. See Figures A.8, A.9, A.10 and A.11.

Reference: Van der Vegt, From Polymers to plastics, VSSD 2006, ISBN 978-90-71301-62-9.

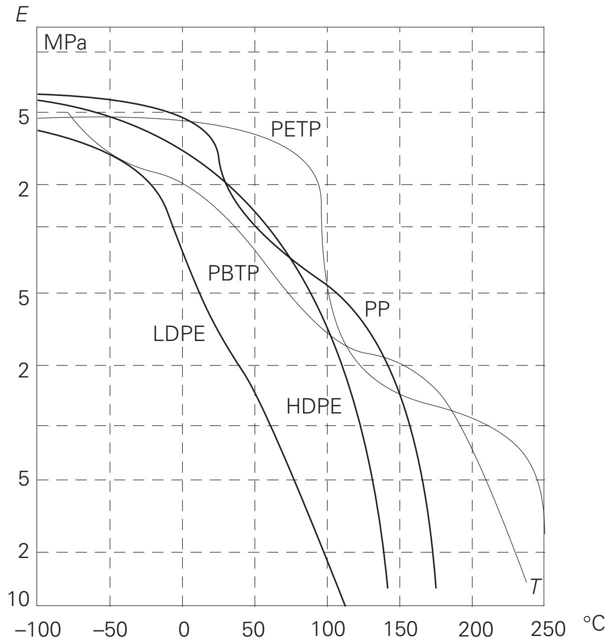


Figure A.9 Youngs modulus, E, as a function of temperature for thermoplasts (Note: E = 10 MPa at y-axis = 10 at a logarithmic scale)

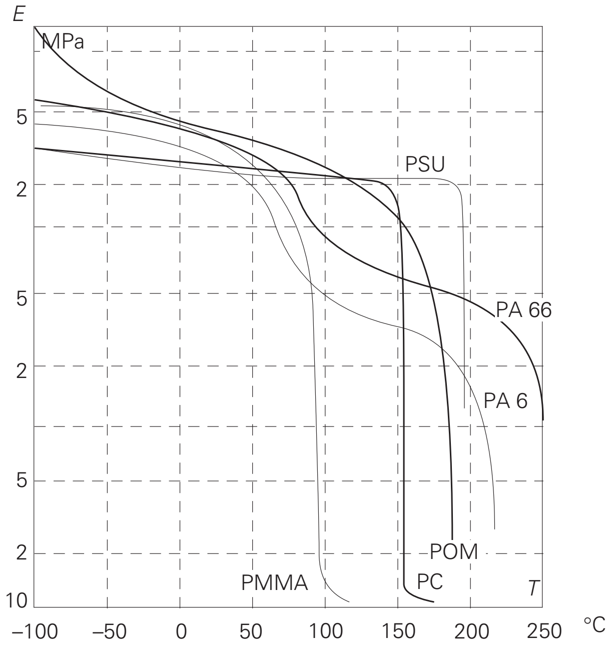


Figure A.10 Youngs modulus, E, as a function of temperature for thermoplasts (Note: E = 10 MPa at y-axis = 10 at a logarithmic scale)

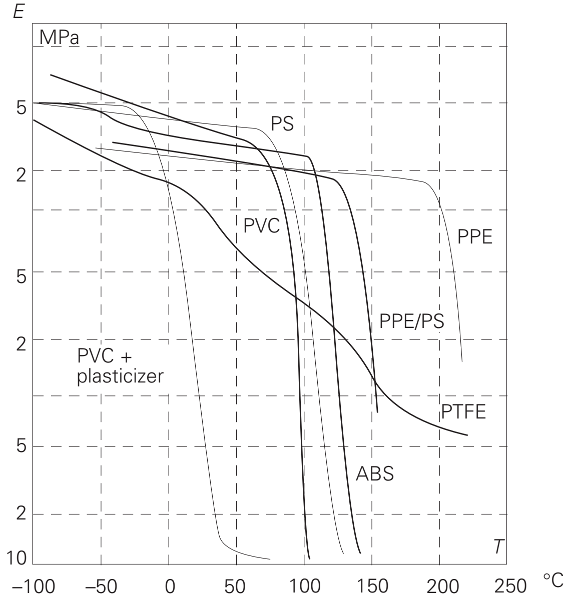


Figure A.11 Youngs modulus, E, as a function of temperature for thermoplasts (Note: E = 10 MPa at y-axis = 10 at a logarithmic scale)

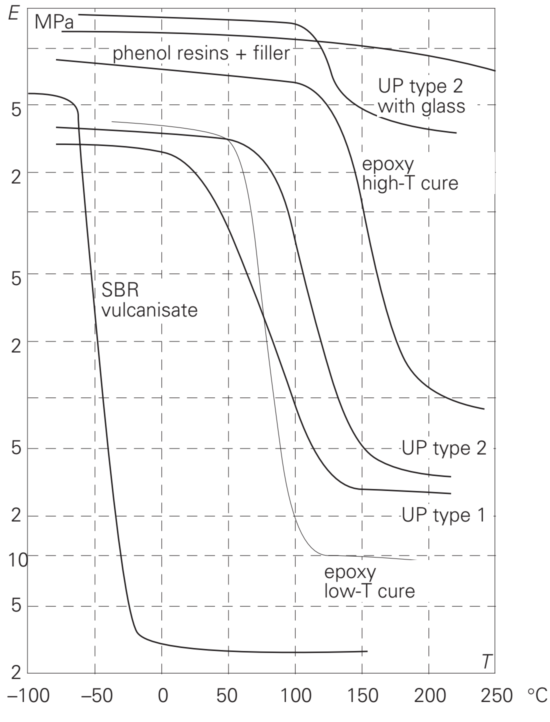


Figure A.12 Youngs modulus, E, as a function of temperature for some thermosets (Note: E = 10 MPa at y-axis = 10 at a logarithmic scale)

Abreviations

ABS	Acrylonitrile-butadiene-styrene copolymer
ASA	Acrylonitrile-styrene-acrylate copolymer
BR	Butadiene rubber
CA	Celluloseacetate
CAB	Celluloseacetate-butyrate
CR	Chloroprene rubber
EP	Epoxy, solid (thermoset)
EPR	Ethylene-propylene rubber
ETFE	Tetrafluorethylene-ethylene copolymer
FEP	Hexafluorpropylene-tetrafluorethylene copolymer
Fl.R	Fluor rubbers
HDPE	Highdensity polyethylene
IIR	Butyl rubber
IR	Isoprene rubber
LDPE	Low density polyethene
MF	Melamineformaldehyde (thermoset)
NBR	Nitrile rubber
NR	Natural rubber
PA 11	Polyamide-11 (nylon-11)
PA 12	Polyamide-12 (nylon-12)
PA 6	Polyamide-6 (nylon-6)
PA 6.6	Polyamide-6.6 (nylon-6.6)
PB	Polybutylene
PBTP	Polybutylene terephtalate
PC	Polycarbonate
PEEK	Polyether-ether-ketone
PES	Polyethersulphone
PETP	Polyethylene terephtalate
PF	phenolformaldehyde (thermoset)
PI	Polyimide
PK	Polyketone
PMMA	Polymethylmethacrylate
PMP	Polymethylpentene
POM	Polyoxymethylene
PP	Polypropylene
PPE	Polyphenyleneether
PPE/PS	Polyphenyleneether + polystyrene

PPS	Polyphenylenesulfide
PS	Polystyrene
PS	Polystyrene
PSU	Polysulfone
PTFE	Polytetrafluorethylene
PUR	Polyurethane rubber
PVC	Polyvinylchloride
PVDF	Polyvinylidenefluoride
SAN	Styrene-acrylonitril copolymer
SBR	Styrene-butadiene rubber
SBS	Thermoplastic rubber
SI	Silicone rubber
TPS	High impact polystyrene
UF	Ureumformaldehyde (thermoset)
UP	Polyester, normal (thermoset)

List of Figures and Tables

References

Ashby, M.F.; Materials and the environment, eco-informed material choice. Elsevier, 2009

Vogtländer, J.G. et al.; LCA-based assessment of sustainability: the Eco-costs/Value Ratio (EVR), VSSD, Delft, 2010

Vogtländer, J.G. et al.; Eco-efficient Value Creation, sustainable strategies fort he circular economy, Delft Academic Press, Delft, Second edition 2014

This data gauide is meant to be used together with the following practical guide on the LCA method:

Vogtländer, J.G; A practical guide to LCA for students, designers and business managers, cradle-to-grave and cradle-to-cradle. VSSD, Delft, Fourth edition 2016

Sustainable Design Series of Delft University of Technology

Life Cycle Assessment (LCA) is a well-defined method to calculate the environmental burden of a product or service.
The recent book "A practical guide to LCA, for students designers and business managers" (Vogtländer, 2016) is an attempt to explain LCA in such a way that students and other interested people (non-experts) can easily and quickly understand how to do the required calculations.
Another hurdle, however, is to acquire the data required for a specific LCA calculation. Although the internet is the modern source of data, there is still a need for data guides that provide data in an easy and accessible way. Especially in labs and workshops, it appears that look-up tables in a reference guide are faster than a search on the internet or searches in big computer databases.
A quick reference guide like this seems to be very useful in the early design phases, when it is essential to have a good overview of alternative design solutions.
This Quick Reference Guide on LCA data provides frequently required data in practice, and gives URLs of where more specific data can be found.

The author's hope is that this book will not only be used by students, but also by designers, architects, and business managers (and their consultants), contributing to the wider awareness that LCA is an indispensible tool in modern design and engineering.

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