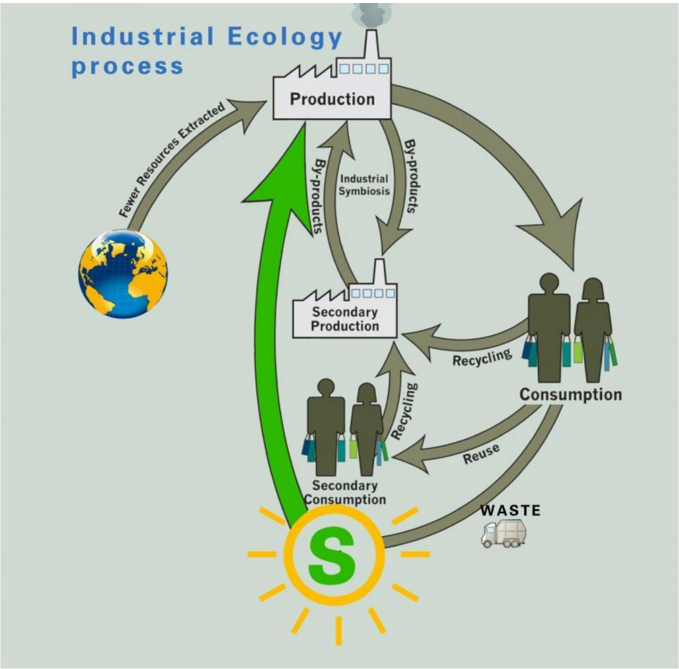
Industrial Ecology – LCA module
1st semester 2013/2014



Carla Silva

E-mail: carla.silva@ist.utl.pt

Principal investigator @ IDMEC

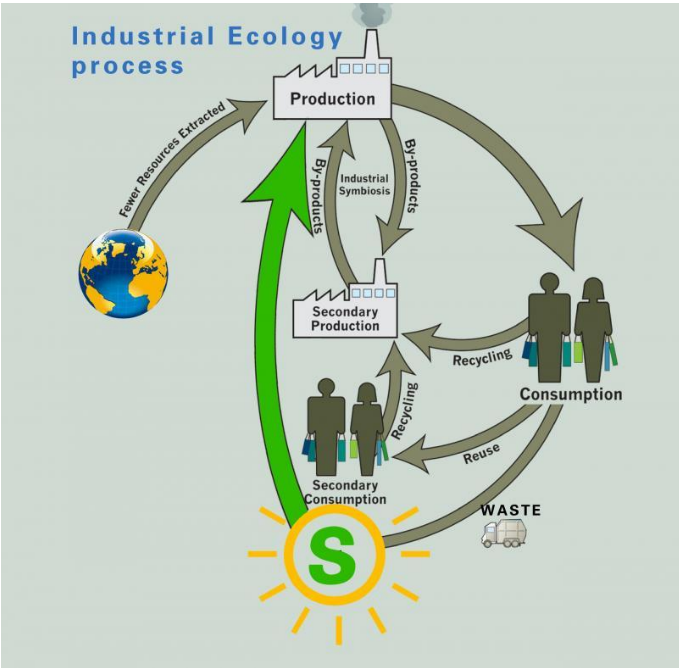
Researcher ID: A-4724-2012

OUTLINE

- Industrial ecology and LCA
- Life cycle notion
- ISO norms steps
- Goal, boundaries, allocation, functional unit?
- What assessments to choose?
- Impact assessment calculation
- Softwares/databases
- Examples

Industrial Ecology

"Industrial metabolism" study of material and energy flows through industrial systems.

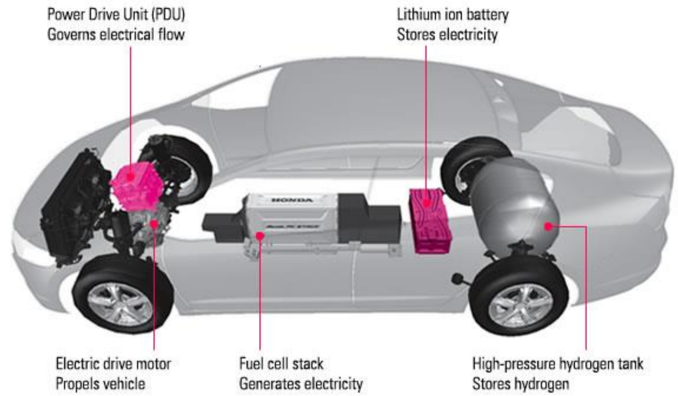


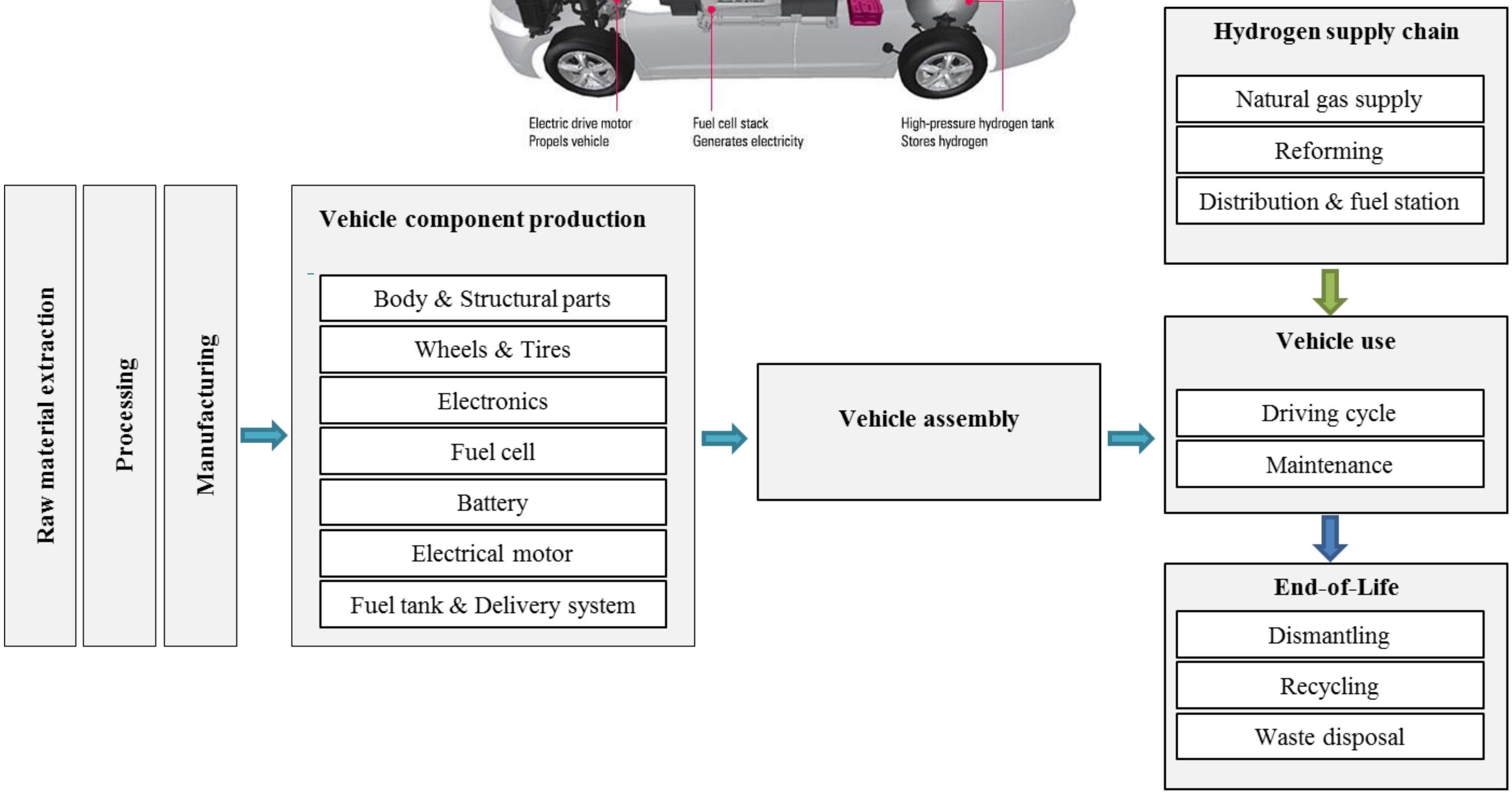
Inputs/Outputs

Sustainability → **Energy**, **Emissions**, **Impact**

"closed loop system where wastes can become inputs for new processes" → **Zero waste**

Life cycle notion



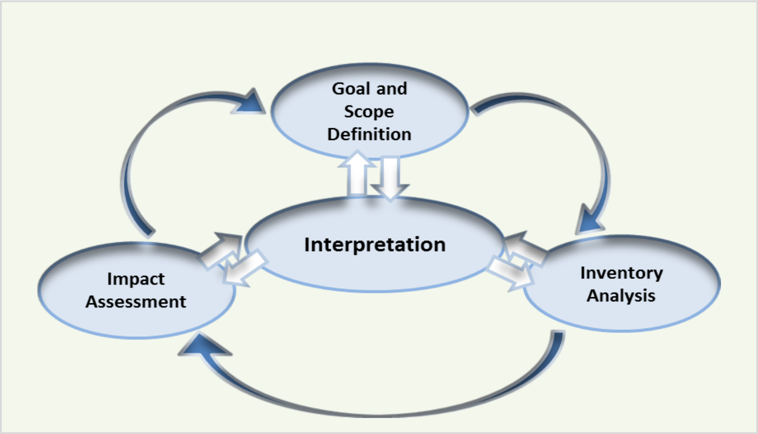


LCA – Life Cycle Analysis

Methodology to assess environmental impacts associated with all the stages of a product's life from cradle-to-grave

- Raw material extraction
- Materials processing
- Manufacture
- Distribution
- Use
- Maintenance
- Disposal or recycling

Steps as in ISO 14040:2006 and 14044:2006



Life Cycle – Goal and scope definition

- **Functional unit***
- **System boundaries;**
- **Assumptions and limitations;**
- **Allocation methods**; and**
- **Impact categories**

→

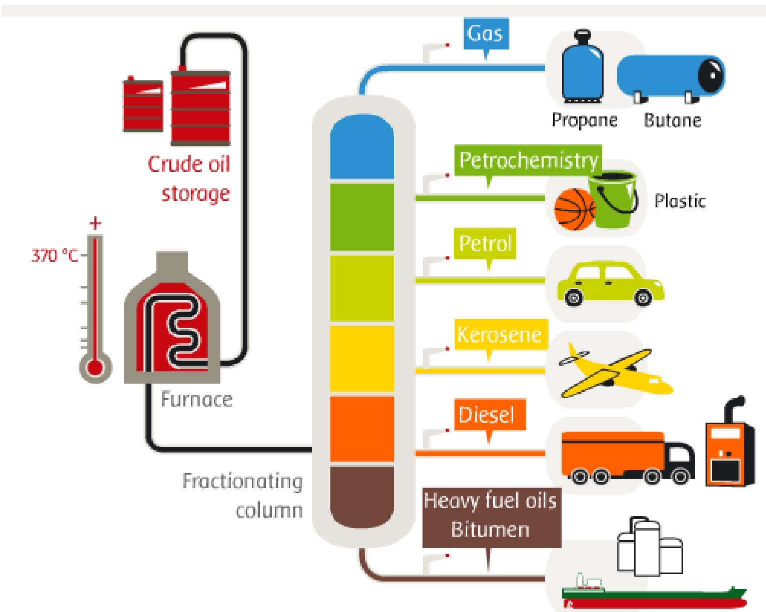
Cradle-to-Grave (CTG)
Cradle-to-Gate (CTG)
Cradle-to-Cradle (CTC)
Gate-to-Gate (GTG)
Well-to-Wheel (WTW)

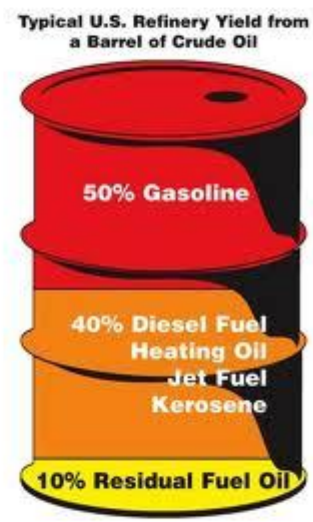
*defines what precisely is being studied and quantifies the service delivered by the product system, providing a reference to which the inputs and outputs can be related; important basis that enables the product to be compared and analyzed

used to partition the environmental load of a process when several products or functions share the same process **mass and economic

Industrial Ecology

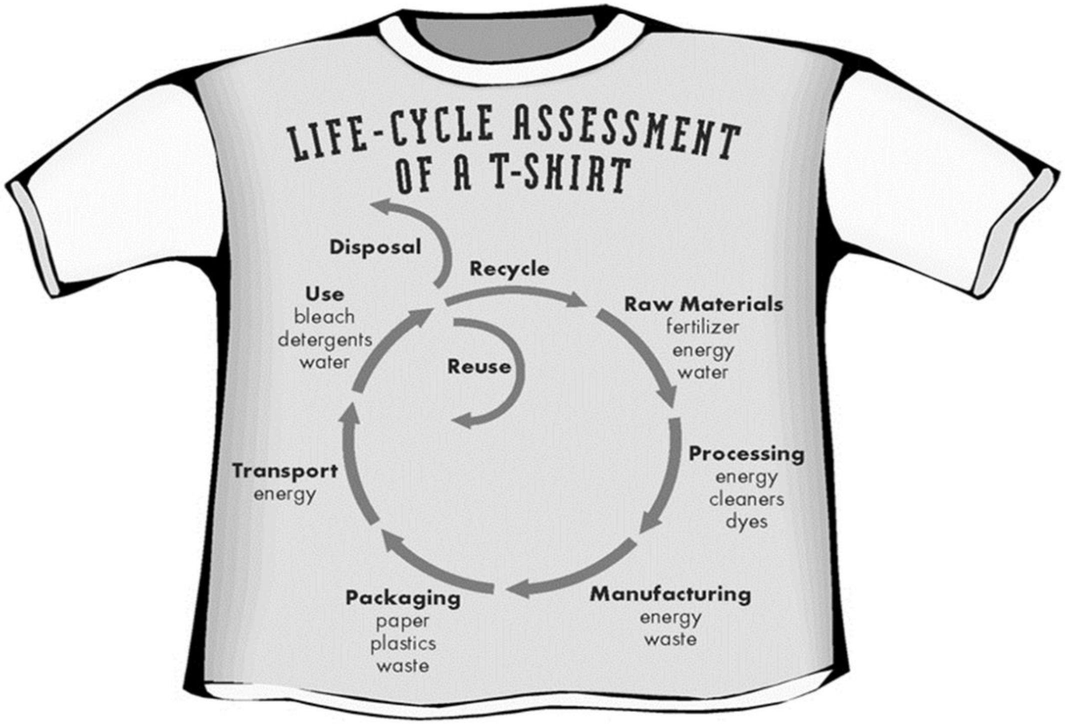
Life Cycle – Goal and scope definition





Life Cycle – Goal and scope definition

Life Cycle – Goal and scope definition



Life Cycle – Inventory

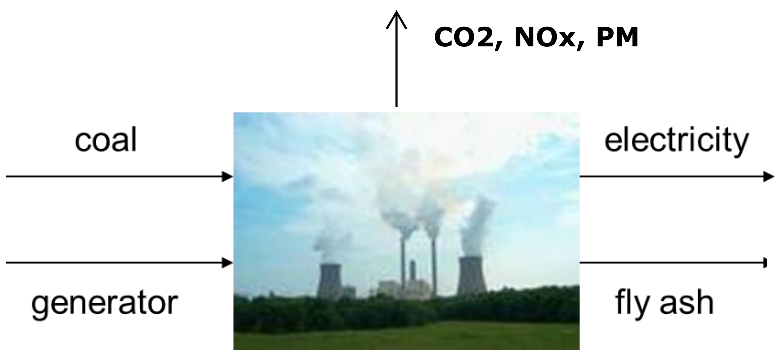
Inputs-Outputs balance

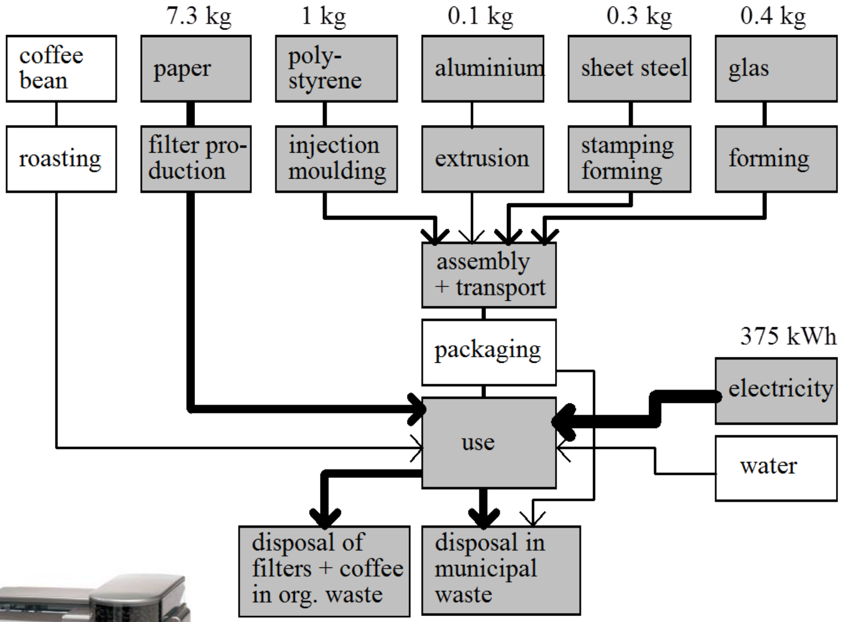
$$Energy = \sum Energy_{eachprocess} / FU$$

$$CO_2 = \sum CO_{2eachprocess} / FU$$

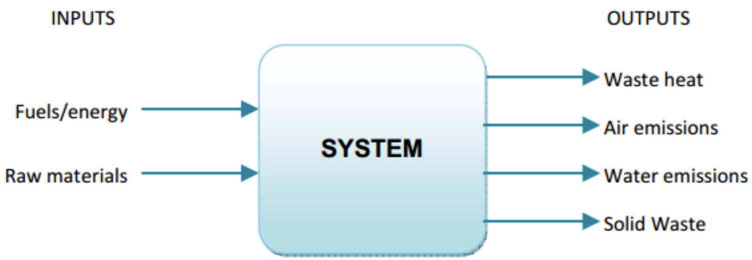
FU – Functional Unit e.g. MJ of final product
kg of final product
passenger.km
km

Life Cycle – Inventory





Life Cycle – Inventory



1 wash/day
75 day
g/day

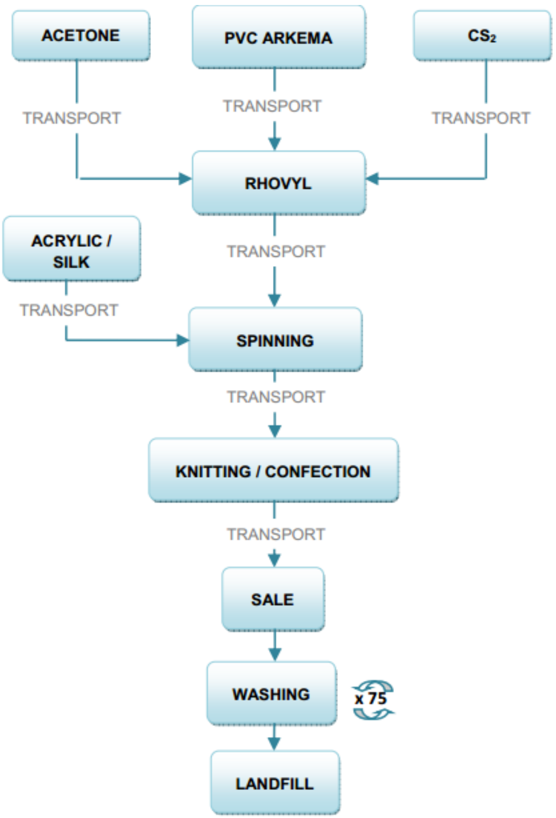
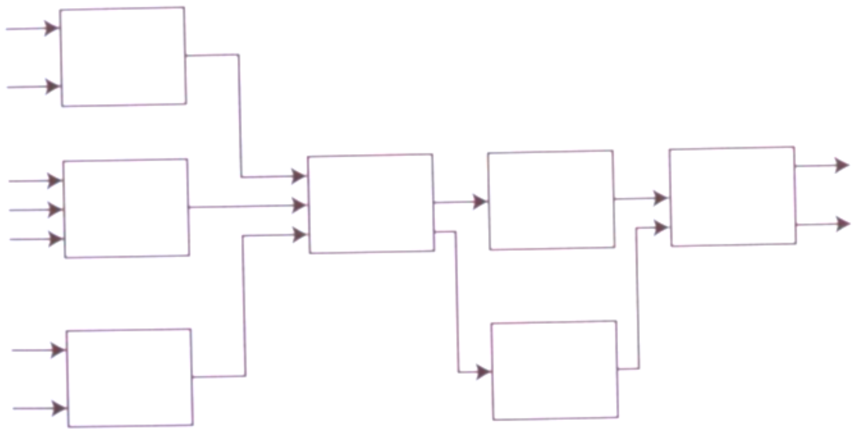


Figure 1. Flow diagram of the t-shirt

Life Cycle – Inventory



Inventory Table	per FU	
CO2	915	g
CH4	1.08	g
N2O	6.37	mg
Halon-1301	53.93	microg
CO	1.74	g
NO2	4.95	g
SO2	2.86	g
NO	3.23	mg
Hydrochloric acid (HCL)	64.63	mg
HF	14.66	mg
Amonia (NH3)	34.86	mg
Ni	808.34	mg
Benzene (C6H6)	7.43	mg
Chromium (Cr)	1.8	microg
PAH	5.95	microg
Cd	12.37	microg
Pb	40.57	mg
Mn	29.62	microg
Hg	2.7	microg
Aldehydes	273.46	microg
NMVOC	2.58	g
dust	1.28	g
Cu	3.72	microg
Zn	615.49	microg
Cr	1.8	microg

 E-mail: carla.silva@ist.utl.pt

Industrial Ecology

Life Cycle – Interpretation/level of confidence in the final results

$$SD_{g95} = \sigma_g^2 = \exp^{\sqrt{[\ln(U_1)]^2+[\ln(U_2)]^2+[\ln(U_3)]^2+[\ln(U_4)]^2+[\ln(U_5)]^2+[\ln(U_6)]^2+[\ln(U_b)]^2}}$$

The factors U1 till U6 referring to the scores in the following table; the factor Ub refers to the basic uncertainty factor. So if you want to assess the impact of reliability (U1), and you have verified, measured data, the value of U1 is equal to 1.00, if you have obtained data from an expert that has done a theoretical calculation and some estimations, you cut give U2 a value of 1.2, etc.

Score:	1	2	3	4	5
U1 Reliability	Verified data based on measurements	Verified data partly based on assumptions OR non-verified data based on measurements	Non-verified data partly based on qualified estimates	Qualified estimate (e.g. by industrial expert); data derived from theoretical information (stoichiometry, enthalpy, etc.)	Non-qualified estimate
	1.00	**1.05**	**1.10**	**1.20**	**1.50**
U2 Completeness	Representative data from all sites relevant for the market considered over an adequate period to even out normal fluctuations	Representative data from >50% of the sites relevant for the market considered over an adequate period to even out normal fluctuations	Representative data from only some sites (<<50%) relevant for the market considered OR >50% of sites but from shorter periods	Representative data from only one site relevant for the market considered OR some sites but from shorter periods	Representativeness unknown or data from a small number of sites AND from shorter periods
	1.00	**1.02**	**1.05**	**1.10**	**1.20**
U3 Temporal correlation	Less than 3 years of difference to our reference year (2000)	Less than 6 years of difference to our reference year (2000)	Less than 10 years of difference to our reference year (2000)	Less than 15 years of difference to our reference year (2000)	Age of data unknown or more than 15 years of difference to our reference year (2000)
	1.00	**1.03**	**1.10**	**1.20**	**1.50**
U4 Geographical correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from smaller area than area under study, or from similar area		Data from unknown OR distinctly different area (north america instead of middle east, OECD-Europe instead of Russia)
	1.00	**1.01**	**1.02**		**1.10**
U5 Further technological correlation	Data from enterprises, processes and materials under study (i.e. identical technology)		Data on related processes or materials but same technology, OR Data from processes and materials under study but from different technology	Data on related processes or materials but different technology, OR data on laboratory scale processes and same technology	Data on related processes or materials but on laboratory scale of different technology
	1.00		**1.20**	**1.50**	**2.00**
U6 Sample size	>100, continous measurement, balance of purchased products	>20	> 10, aggregated figure in env. report	>=3	unknown
	1.00	**1.02**	**1.05**	**1.10**	**1.20**

In all ecoinvent Unit process data, you will find a list of six figures, like 1.2.1.5.1.3 in each comment field. These numbers refer to how the uncertainty was estimated using the pedigree matrix. Please not that you will not find any uncertainty data in the System processes

The *basic* uncertainty factor Ub can de derived from the table below. This basic uncertainty factor is based on expert judgement. For instance, experts often find that CO_2 emission data can be quite precise, and can be easily checked against the fuel input. As you can see the basic uncertainty is assumed to be very high for poly aromatic hydrocarbons (PAH), Fine dust (PM10 and PM2.5) and heavy metal emissions, as well as radionuclides and CO from combustion.

input / output group	Ub	input / output group	Ub
demand of:		**emission to air of:**	
thermal energy	1.05	CO2	1.05
electricity	1.05	SO2	1.05
semi-finished products	1.05	combustion: NOX, NMVOC total, methane, N2O and NH3	1.50
working materials	1.05	Combustion: CO	5.00
transport services	2.00	Combustion: individual hydrocarbons, TSM	1.50
waste treatment services	1.05	Combustion: PM10	2.00
Infrastructure	3.00	Combustion: PM2.5	3.00
resources:		combustion: polycyclic aromatic hydrocarbons (PAH)	3.00
primary energy carriers	1.05	Combustion: heavy metals	5.00
metals, salts	1.05	process emissions: individual VOCs	2.00
land use, occupation	1.50	process emissions: CO2	1.05
land use, transformation	2.00	process emissions: TSM	1.50
waste heat:		process emissions: PM10	2.00
emission to air, water, and soil	1.05	process emissions: PM2.5	3.00
emission to water of:		from agriculture: CH4, NH3	1.20
BOD, COD, DOC, TOC	1.50	from agriculture: N2O, NOX	1.40
inorganic compounds (NH4, PO4, NO3, Cl, Na etc.)	1.50	radionucleides (e.g., Radon-222)	3.00
individual hydrocarbons, PAH	3.00	process emissions: other inorganic emissions	1.50
heavy metals	5.00	**Emission to soil of:**	
from agriculture: NO3, PO4	1.50	oil, hydrocarbon total	1.50
from agriculture: heavy metals	1.80	Pesticides	1.20
from agriculture: pesticides	1.50	heavy metals	1.50
radionucleides	3.00	radionucleides	3.00

(taken from: Ecoinvent report number 1: Overview and methodology)

Carl

E-mail: carla.silva@ist.utl.pt

Life Cycle – Impact Assessment

- **Selection of impact categories, category indicators, and characterization models;**
- **Classification stage, where the inventory parameters are sorted and assigned to specific impact categories;**
- **Impact measurement, where the categorized LCI flows are characterized, using one of many possible LCIA methodologies, into common equivalence units that are then summed to provide an overall impact category total.**

 E-mail: carla.silva@ist.utl.pt

Life Cycle – Impact Assessment

LCIA methodologies

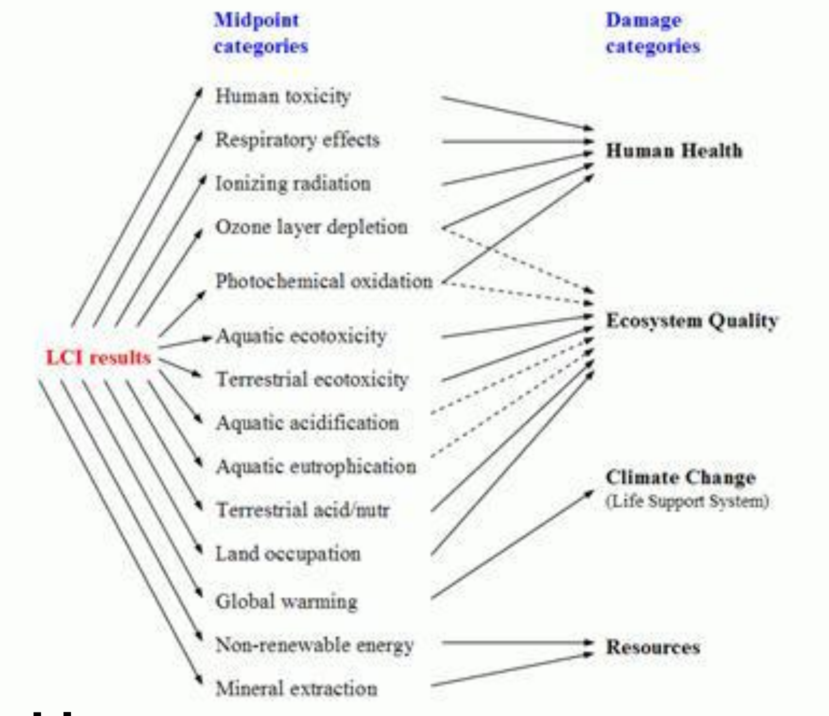
http://lct.jrc.ec.europa.eu/pdf-directory/Recommendation-of-methods-for-LCIA-def.pdf

climate change, ozone depletion, eutrophication, acidification, human toxicity (cancer and non-cancer related), respiratory inorganics, ionizing radiation, ecotoxicity, photochemical ozone formation, land use, and resource depletion

- **human health**
- **natural environment**
- **natural resource use**

Life Cycle – Impact Assessment

problem-oriented (mid points) **damage-oriented (end points)**



e.g. Procter & Gamble ….

"It is important to understand both the advantages and limitations of the conversion in order to interpret the indicators properly and reach sound conclusions."

Life Cycle – Impact Assessment

LCIA methodologies

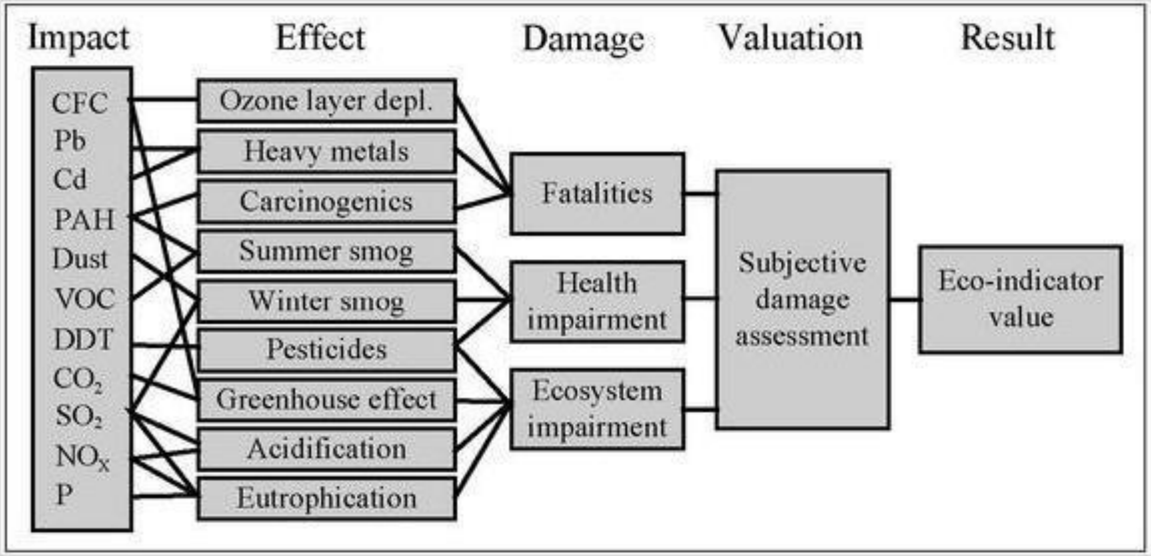
- ReCiPe
- BEES
- Eco-indicator 99
- Eco-indicator 95
- CML 92
- CML 2001
- Ecosystem Damage Potential
- EDIP/UMIP
- EDIP 2003
- EPS 2000
- EPD2007
- Ecopoints 97
- Impact 2002+
- TRACI
- EPD method
- Cumulative Energy Demand
- Cumulative Exergy Demand
- IPCC Greenhouse gas emissions
- IPCC2007
- Ecological Footprint
- Eco Scarcity 2006
- Selected LCI's

Eco-Indicator 99
Eco-Indicator 95
CML 2001
Impact 2002

 E-mail: carla.silva@ist.utl.pt

Life Cycle – Impact Assessment

Eco-Indicator



Bertoluci, G., & Millet, D. (2008). Functional product enrichment and supply chain disorganisation: two barriers for sustainable design [Figure 5]. International Journal of Product Development, 7, 149-169. Publisher: Inderscience Publishers Ltd.

Life Cycle – Impact Assessment

Climate change (global warming potential 20/100/500 years)

$$CO_2 \text{ eq [kg]} = \sum_i^n (GWP_{100} * \text{Emissioni [kg]})$$

Intergovernmental Panel on Climate Change (IPCC)

Industrial Designation or Common Name (years)	Chemical Formula	Lifetime (years)	RadiativeEfficiency (W m^{-2} ppb^{-1})	Global Warming Potential for Given Time Horizon			
				SAR‡ (100-yr)	20-yr	100-yr	500-yr
Carbon dioxide	CO_2	See below[a]	[b] $1.4x10^{-5}$	1	1	1	1
Methane[c]	CH_4	12[c]	$3.7x10^{-4}$	21	72	25	7.6
Nitrous oxide	N_2O	114	$3.03x10^{-3}$	310	289	298	153
Substances controlled by the Montreal Protocol							
CFC-11	CCl_3F	45	0.25	3,800	6,730	4,750	1,620
CFC-12	CCl_2F_2	100	0.32	8,100	11,000	10,900	5,200
CFC-13	$CClF_3$	640	0.25		10,800	14,400	16,400
CFC-113	CCl_2FCClF_2	85	0.3	4,800	6,540	6,130	2,700
CFC-114	$CClF_2CClF_2$	300	0.31		8,040	10,000	8,730
CFC-115	$CClF_2CF_3$	1,700	0.18		5,310	7,370	9,990
Halon-1301	$CBrF_3$	65	0.32	5,400	8,480	7,140	2,760
Halon-1211	$CBrClF_2$	16	0.3		4,750	1,890	575
Halon-2402	$CBrF_2CBrF_2$	20	0.33		3,680	1,640	503
Carbon tetrachloride	CCl_4	26	0.13	1,400	2,700	1,400	435

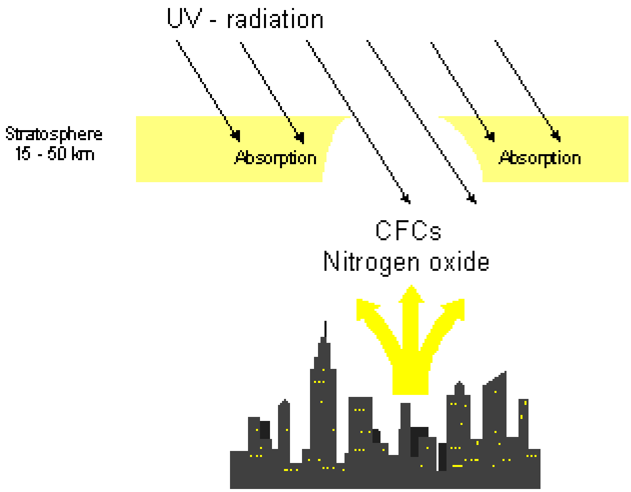
Life Cycle – Impact Assessment

Ozone depletion *ref CFC-11*

ozone depletion potential (ODP)

$$\text{CFC-11}_{eq}[kg] = \sum_i^n (\text{ODP} * \text{Emissioni [kg]})$$

Stratospheric Ozone Depletion			
Ethane, 1-chloro-1,1-difluoro-, HCFC-142	000075-68-3	0.043	kg CFC-11 eq / kg
Ethane, 1,1-dichloro-1-fluoro-, HCFC-141b	001717-00-6	0.086	kg CFC-11 eq / kg
Ethane, 1,1,1-trichloro-, HCFC-140	000071-55-6	0.11	kg CFC-11 eq / kg
Ethane, 1,1,1-trifluoro-2,2-chlorobromo-, Halon 2311	000151-67-7	0.14	kg CFC-11 eq / kg
Ethane, 1,1,1,2-tetrafluoro-2-bromo-, Halon 2401	000124-72-1	0.25	kg CFC-11 eq / kg
Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	000076-13-1	0.9	kg CFC-11 eq / kg
Ethane, 1,2-dibromotetrafluoro-, Halon 2402	000124-73-2	7	kg CFC-11 eq / kg
Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	000076-14-2	0.85	kg CFC-11 eq / kg
Ethane, 2-chloro-1,1,1,2-tetra-fluoro-, HCFC-124	002837-89-0	0.026	kg CFC-11 eq / kg
Ethane, 2,2-dichloro-1,1,1-tri-fluoro-, HCFC-123	000306-83-2	0.012	kg CFC-11 eq / kg
Ethane, chloropentafluoro-, CFC-115	000076-15-3	0.4	kg CFC-11 eq / kg
Methane, bromo-, Halon 1001	000074-83-9	0.37	kg CFC-11 eq / kg
Methane, bromochlorodifluoro-, Halon 1211	000353-59-3	5.1	kg CFC-11 eq / kg
Methane, bromodifluoro-, Halon 1201	001511-62-2	1.4	kg CFC-11 eq / kg
Methane, bromotrifluoro-, Halon 1301	000075-63-8	12	kg CFC-11 eq / kg
Methane, chlorodifluoro-, HCFC-22	000075-45-6	0.034	kg CFC-11 eq / kg
Methane, dibromodifluoro-, Halon 1202	000075-61-6	1.25	kg CFC-11 eq / kg
Methane, dichlorodifluoro-, CFC-12	000075-71-8	0.82	kg CFC-11 eq / kg
Methane, monochloro-, R-40	000074-87-3	0.02	kg CFC-11 eq / kg
Methane, tetrachloro-, CFC-10	000056-23-5	1.2	kg CFC-11 eq / kg
Methane, trichlorofluoro-, CFC-11	000075-69-4	1	kg CFC-11 eq / kg
Propane, 1,3-dichloro-1,1,2,2,3-pentafluoro-, HCFC-225cb	000507-55-1	0.017	kg CFC-11 eq / kg
Propane, 3,3-dichloro-1,1,1,2,2-pentafluoro-, HCFC-225ca	000422-56-0	0.017	kg CFC-11 eq / kg



E-mail: carla.silva@ist.utl.pt

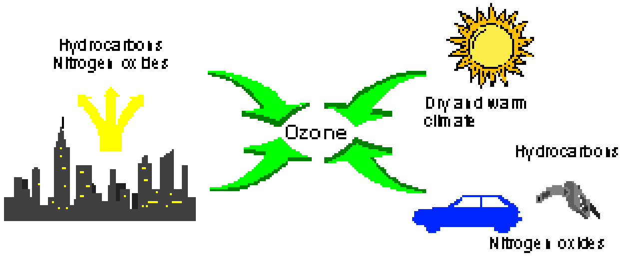
Life Cycle – Impact Assessment

Summer Smog *ref C_2H_4*

photochemical ozone creation potential (POCP) indicates the potential capacity of a volatile organic substance to produce ozone

Smog (kg) = (POCP x airborne emission (kg))

Pollutant species (MELCHIOR compound)	Corresponding item in life cycle inventory	$POCP_{mean}$	$POCP_{AOT40}$	$POCP_{AOT60}$	$POCP_{AOT90}$	$POCP_{peak}$
CO	Carbon monoxide	2.0	1.9	2.3	2.2	1.8
C_2H_6	Ethane	2.1	3.3	4.8	5.9	3.1
NC_4H_{10}	Other alkanes	10	15	19	22	14
C_2H_4	Ethene (ethylene)	100	100	100	100	100
C_3H_6	Other alkenes	67	75	82	91	76
C_5H_8	Isoprene	23	33	39	30	29
APINEN	Terpenes	2.2	11	15	16	9
Oxyl	Aromatics HC, phenols	44	53	59	68	54
HCHO	Formaldehyde	41	43	40	45	43
CH_3CHO	Other aldehydes	6.3	11	20	23	11
CH_3COE	Ketones	6.7	14	17	21	14
TOTVOC	Total VOC	21	27	32	34	26
NO_x	Nitrogen oxides	95	59	66	27	50



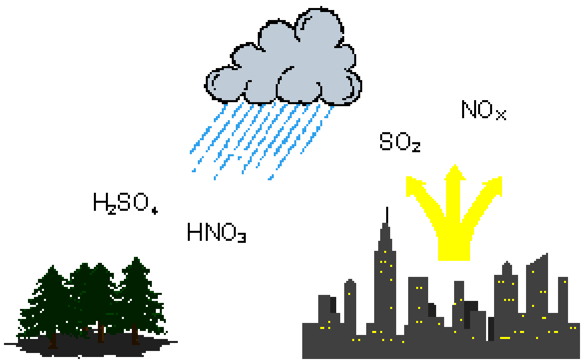
Life Cycle – Impact Assessment

Acidification

$$\text{Acidification (kg)} = \left(\text{AP x airborne emission (kg)}\right)$$

Substance	Acidification potential (AP_i in kg SO_2-equiv./kg)
SO_2	1.00
NO	1.07
N_2O	0.70
NO_x	0.70
NH_3	1.88
HCl	0.88
HF	1.60

ref SO_2



 E-mail: carla.silva@ist.utl.pt

Life Cycle – Impact Assessment

Human toxicity The degree to which a chemical substance elicits a deleterious or adverse effect upon the biological system of human exposed to the substance over a designated time period.

$$\text{Human toxicity (kg)} = \left(\text{HCA (kg.kg}^{-1}\text{) x emission to air (kg)} + \text{HCW (kg.kg}^{-1}\text{) x emission to water (kg)}\right)^5$$

Burden	Human Toxicity Potential
CO (carbon monoxide)	0.012
NO_x (oxides of nitrogen)	0.78
SO_2 (sulphur dioxide)	1.2
Hydrocarbons (excluding methane)	1.7
Chlorinated hydrocarbons	0.98
Chlorofluorocarbons	0.022
As (arsenic vapour)	4700
Hg (mercury vapour)	120
F_2 (fluorine)	0.48
HF (hydrogen fluoride)	0.48
NH_3 (ammonia)	0.0017-0.020
As (arsenic as solids)	1.4
Cr (chromium)	0.57
Cu (copper)	0.02
Fe (iron)	0.0036
Hg (mercury as liquid)	4.7
Ni (nickel)	0.057
Pb (lead)	0.79
Zn (zinc)	0.0029
Fluorides	0.041
Nitrates	0.00078
Phosphates	0.00004

Life Cycle – Impact Assessment

Carcinogenic

The 'Air Quality Guidelines' do not specify acceptable levels, but calculate the probability of cancer at a level of 1 μg/m³. In the table below this probability is expressed as the number of people from a group of 1 million who will develop cancer with the stated exposure. (Polycyclic aromatic hydrocarbons (PAHs))

	Probability of cancer at 1 μg/m³	Weighting factor for PAH equivalent	Type of cancer
Arsenic	0.004	0.044	General, also mutagenic effects
Benzene	0.000001	$1.1 * 10^{-5}$	Leukaemia
Nickel	0.04	0.44	Lung and larynx
Chromium (VI)	0.04	0.44	Lung, among others, and mutagenic effects
PAHs (benzo(a)pyrene)	0.09	1	Lung cancer but also other types of cancer

$$\textbf{Carcinogenic eq [kg]} = \sum_i^n (\textbf{WF} * \textbf{Emissioni [kg]})$$

E-mail: carla.silva@ist.utl.pt

Life Cycle – Impact Assessment

Heavy Metals high atomic weight

WF

Heavy metal to air (kg lead eq.) = (AQG (lead)/AQG (substance) * emission)

Heavy metal to water (kg lead eq.) = (GDWQ (lead)/GDWQ (substance)* emission)

Air Quality Guidelines

	Maximum concentration (μg/m³)	Weighting factor	Main health effect
Cadmium	0.02	50	Kidneys
Lead	1	1	Blood biosynthesis, nervous system and blood pressure
Manganese	7	0.14	Lungs and nervous system (shortage cause skin complaints)
Mercury	1	1	Brain: sensory and co-ordination functions

Water Quality Guidelines

Substance	Norm (mg/litre)	Weighting factor	Effect
Antimony	0.005	2	Glucose and cholesterol content of blood
Arsenic	0.01	1	Probability of skin cancer $6*10^{-4}$
Barium	0.07	0.14	Blood pressure and blood vessels
Boron	0.3	0.03	Fertility
Cadmium	0.003	3	Kidneys
Chromium (all)	0.05	0.2	Heredity (carcinogenity only applicable in event of inhalation)
Copper	2	0.005	Generally no problems, sometimes liver abnormalities
Lead	0.01	1	Blood biosynthesis, nervous system and blood pressure
Manganese	0.5	0.02	Nervous system
Mercury	0.001	10	Kidneys, nervous system (methyl mercury)
Molybdenum	0.07	0.14	No clear description
Nickel	0.02	0.5	Weight loss, great uncertainty

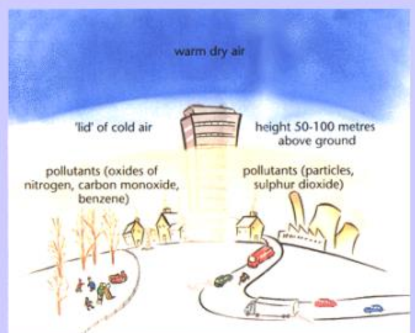
E-mail: carla.silva@ist.utl.pt

Life Cycle – Impact Assessment

Winter Smog

Only dust (SPM) and SO_2 are factors in this problem. For both substances the 'Air Quality Guidelines' specify a level of 50 μg/m³. The weighting factors are thus both 1.

Winter smog (SO_2 or SPM eq.) = SO2 emission + SPM emission



Caused by mixture of pollutants from:

- **road vehicles**
- **fuels used to provide electricity and heating in offices, factories and homes**

Formed by:
Pollutants building up at ground level in urban areas. The 'lid' of cold air above the warm air traps the pollutants

When:
On cold, calm days, often after a clear, cloudless night and an early-morning frost or mist close to the ground

Life Cycle – Impact Assessment

Eutrophication

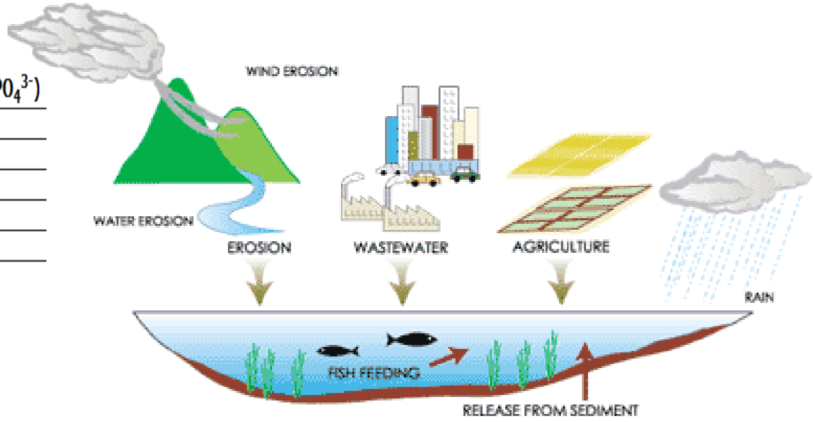
enrichment of aquatic systems with nutrients

The Nutriphication Potential (NP) is set at 1 for phosphate (PO_4). Other emissions also influence eutrophication, notably nitrogen oxides and ammonium.

The eutrophication effect score is calculated as follows:

$$\text{Eutrophication (kg)} = \left(\text{NP x airborne emission (kg)}\right)$$

Burden	Eutrophication Potential (*vs* PO_4^{3-})
Phosphates	1
Nitrates	0.42
Ammonia	0.33
Oxides of nitrogen	0.13
Chemical Oxygen Demand (COD)	0.022



 E-mail: carla.silva@ist.utl.pt

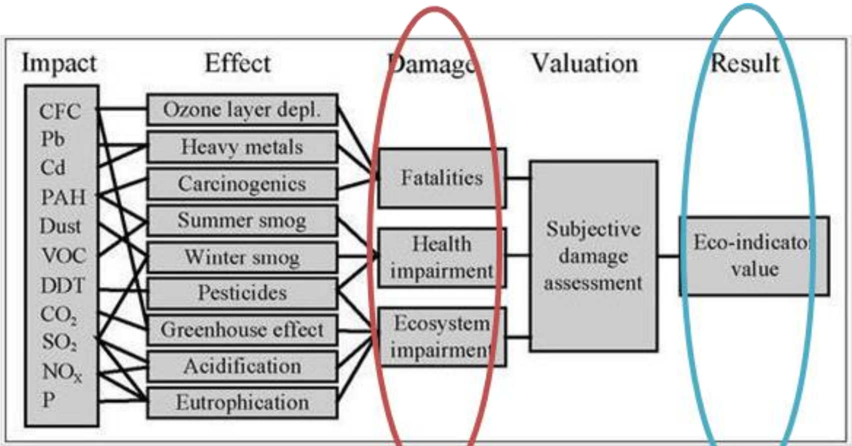
Life Cycle – Impact Assessment

Resource depletion

Exhaustion = (amount consumed (kg) x {1/resources (kg)})

 E-mail: carla.silva@ist.utl.pt

Life Cycle – Impact Assessment



Bertoluci, G., & Millet, D. (2008). Functional product enrichment and supply chain disorganisation: two barriers for sustainable design [Figure 5]. International Journal of Product Development, 7, 149-169. Publisher: Inderscience Publishers Ltd.

Weighting

Normalisation is strongly recommended by CML, suggesting also choosing the whole world or an average world citizen for one year as reference system for all impact categories.

Impact categories	Netherlands, 1997	West-Europe, 1995	World, 1995
Depletion of abiotic resources, kg antimony.yr^{-1}.cap^{-1}	110	32.6	27.7
Climate change, kg CO_{2eq}.yr^{-1}.cap^{-1}	16 100	14 600	6 830
Stratospheric ozone depletion, kg CFC_{11eq}.yr^{-1}.cap^{-1}	0,0626	0,256	0,0911
Human toxicity, kg 1,4-DCB_{eq}.yr^{-1}.cap^{-1}	12 100	23 300	8 800
Fresh water aquatic ecotoxicity, kg 1,4-DCB_{eq}.yr^{-1}.cap^{-1}	483	1550	359
Marine ecotoxicity, kg 1,4-DCB_{eq}.yr^{-1}.cap^{-1}	2,73E+05	3,49E+05	9,05E+05
Terrestrial ecotoxicity, kg 1,4-DCB_{eq}.yr^{-1}.cap^{-1}	61,5	146	47,4
Photo-oxidant formation, kg C_2H_{4eq}.yr^{-1}.cap^{-1}	11,7	25,4	8,04
Acidification, kg SO_{2eq}.yr^{-1}.cap^{-1}	42,9	84,2	52,9
Eutrophication, kg $PO_4^{3-}{}_{eq}$.yr^{-1}.cap^{-1}	32,1	38,4	22,8

	Unit	Western Europe	Eastern Europe	Total	Per head of the population	Uncer-tainty
Greenhouse effect	GWP kg	4.8E+12	1.7E+12	6.5E+12	**1.31E+04**	small
Ozone layer depletion	ODP kg	3.7E+08	9.4E+07	4.6E+08	**9.26E-01**	large
Acidification	AP kg	3.5E+10	2.1E+10	5.6E+10	**1.13E+02**	small
Eutrophication	NP kg	1.4E+10	5.1E+09	1.9E+10	**3.82E+01**	mod.
Heavy metals	Pb equiv. kg	2.1E+07	5.9E+06	2.7E+07	**5.43E-02**	large
Carcinogens	PAH equiv. kg	4.3E+06	1.1E+06	5.4E+06	**1.09E-02**	large
Winter smog	SO2 equiv. kg	2.3E+10	2.3E+10	4.7E+10	**9.46E+01**	small
Summer smog	POCP kg	7.0E+09	1.9E+09	8.9E+09	**1.79E+01**	large
Pesticides	active ingr. kg	3.8E+08	9.8E+07	4.8E+08	**9.66E-01**	large

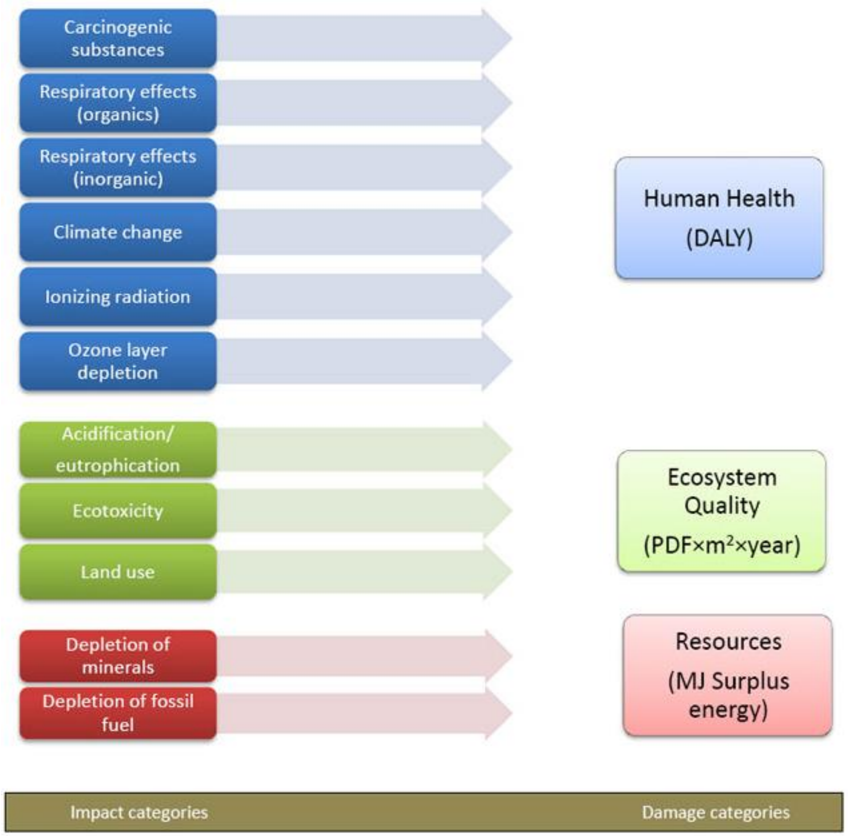
Reference for normalization European value per year 1990

Environmental effect	Weighting factor	Criterion
Greenhouse effect	2.5	0.1°C rise every 10 years, 5% ecosystem degradation
Ozone layer depletion	100	Probability of 1 fatality per year per million inhabitants
Acidification	10	5% ecosystem degradation
Eutrophication	5	Rivers and lakes, degradation of an unknown number of aquatic ecosystems (5% degradation)
Summer smog	2.5	Occurrence of smog periods, health complaints, particularly am... ag...
Winter smog	5	Oc... am...
Pesticides	25	5%...
Airborne heavy metals	5	Lead content in children's blood, reduced life expectancy and learning performance in an unknown number of people
Waterborne heavy metals	5	Cadmium content in rivers, ultimately also impacts on people (see airborne)
Carcinogenic substances	10	Probability of 1 fatality per year per million people

The underlying premise is that there is a correlation between the seriousness of an effect and the distance between the current level and the target level. Thus if acidification has to be reduced by a factor of 10 in order to achieve a sustainable society and smog by a factor of 5, then acidification is regarded as being twice as serious; the reduction factor is the weighting factor. This principle has been refined and improved in the project, but there is

$$\text{WeightedIndex} = \sum_{cat} \text{WeightingFact}_{cat} \times \text{NormalizedndicatorResult}_{cat}$$

EcoIndicator99



(Disability Adjusted Life Years), which is the number of disability years caused by exposure to toxic material multiplied by the "disability factor", a number between 0 and 1 that describes severity of the damage (0 for being perfectly healthy and 1 for being fatal). Per individual.

(Potentially Disappeared Fraction), which is a probability of the plants species to disappear from the area as a result of acidification and eutrophication. Since it is not possible to determine whether the damage is caused by changes in the nutrient level or by acidity, these two impact categories are combined. Land use is also characterized by PDF, which refers to the change in the numbers of all species on the occupied land and at the natural area in the surroundings. The total units of the Ecosystem Quality are PDF times area times year [PDF×m2×year].

"surplus energy" in MJ per kg extracted material, and it is related to the expected increase of extraction energy per kg of extracted material.

Weighting

Perspectief of basishouding	Time perspective	Manageability	Required level of evidence
H (Hierarchist)	Balance between short and long term	Proper policy can avoid many problems	Inclusion based on consensus
I (Individualist)	Short time	Technology can avoid many problems	Only proven effects
E (Egalitarain)	Very long term	Problems can lead to catastrophy	All possible effects

a=yr/yr

	Hierachist (EI'99 H/A)		Egalitarian (EI'99 E/E)		Individualist (EI'99 I/I)	
	Normalisation	Weights	Normalisation	Weights	Normalisation	Weights
Human Health	0.0154 DALYs(0,0)	40%	0.0155 DALYs(0,0)	30%	0.00825 DALYs(0,1)	55%
Ecosystem Quality	5130 PDF*m2*a	40%	5130 PDF*m2*a	50%	4510 PDF*m2*a	25%
Resources	8410 MJ	20%	5940 MJ	20%	150 MJ	20%

Tools/Software

http://lca.jrc.ec.europa.eu/lcainfohub/toolList.vm

Boustead	www.boustead-consulting.co.uk
Eco-it	www.pre.nl
Ecopro	www.sinum.com
Ecoscan	www.ind.tno.nl
Euklid	www.ivv.fhg.de
KCL Eco	www.kcl.fi/eco
Gabi	www.gabi-software.com
LCAit	www.ekologik.cit.chalmers.se
Miet	www.leidenuniv.nl/cml/ssp/software
Pems	www.piranet.com/pack/lca_software.htm
SimaPro	www.pre.nl
Team	www.ecobilan.com
Wisard	www.pwcglobal.com
Umberto	www.umberto.de

Generic

Car specific

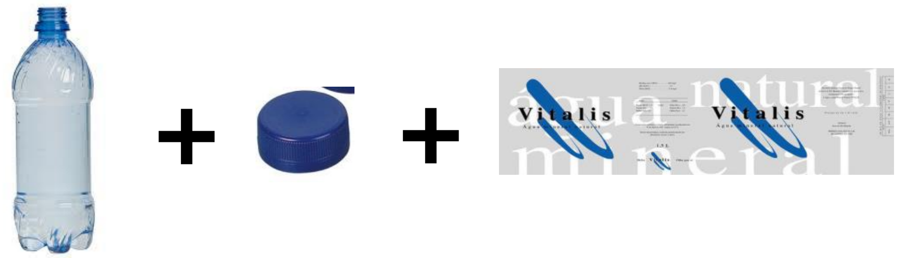
GEMIS	http://www.oeko.de/service/gemis/en/material.htm
GREET	http://greet.es.anl.gov/
LEM	http://www.its.ucdavis.edu/
Optiresource	http://www.optiresource.org

Industrial Ecology

SIMAPRO

Compare the environmental impact of 3 products to provide mineral water:

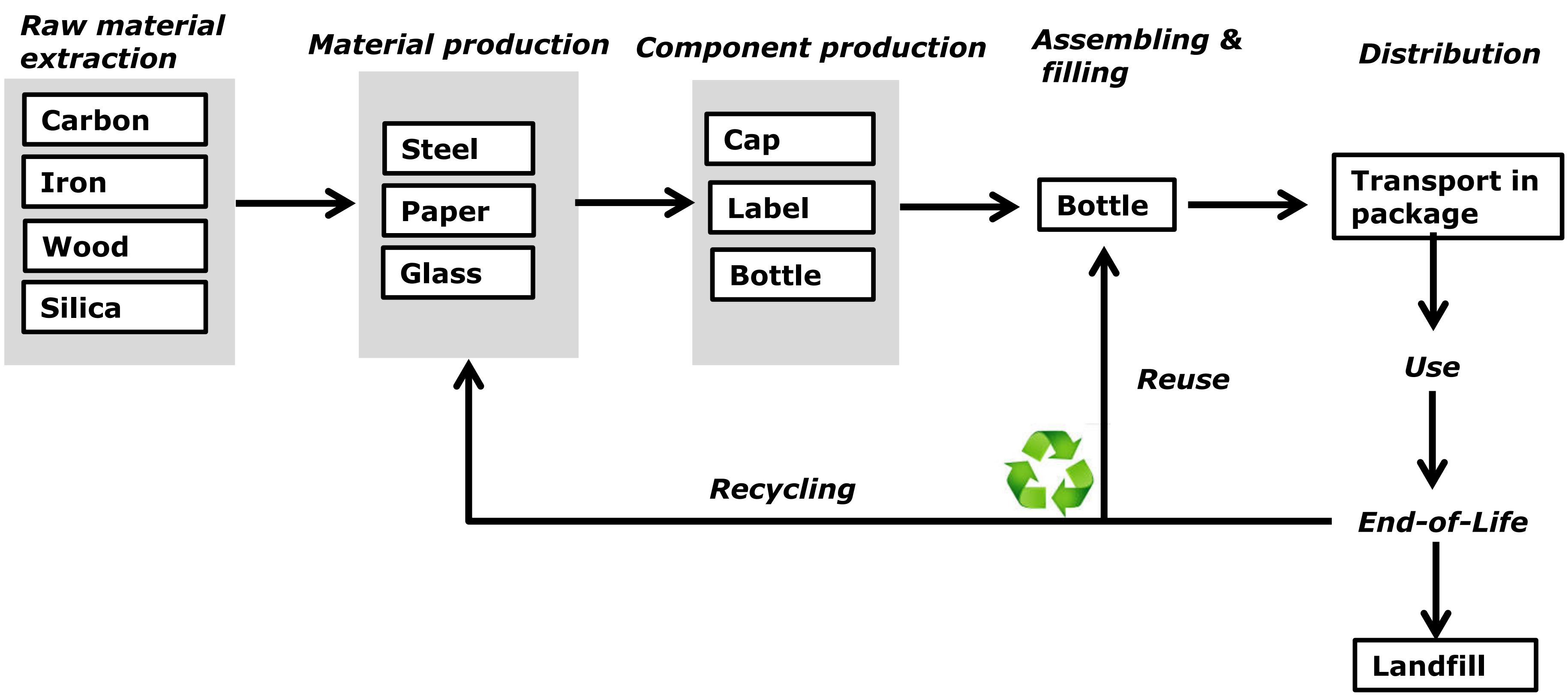
1 glass bottle not reusable;
1 glass bottle reusable;
1 plastic bottle PET (poly(ethylene terephthalate))



Industrial Ecology

SIMAPRO

Simplified life cycle for reusable glass bottle



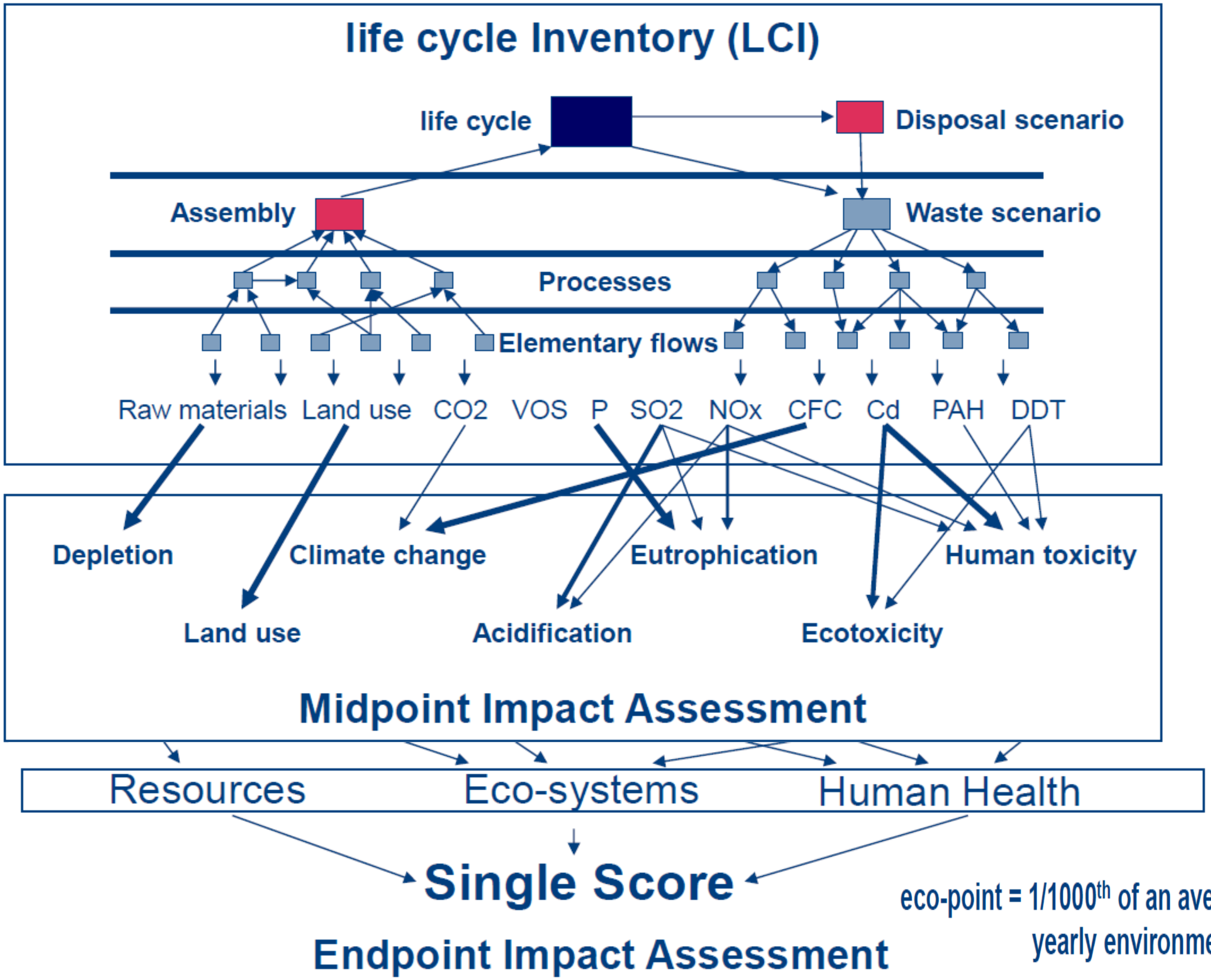
SIMAPRO

Product	Bottle	Cap	Label	Package
1 glass bottle reusable	Glass 599 g	Steel 2.2 g	Paper 1 g	PEHD 1818 g (12 bottle)
1 glass bottle not "	Glass 599 g	Steel 2.2 g	Paper 1 g	Paperboard 519 g (12 bottle)
1 plastic bottle PET	PET 18 g	PEHD 2.5 g	Paper 1 g	PELD 38 g

HD-High Density; LD-Low Density; PE- PolyEthylen; * Relatively to the market available

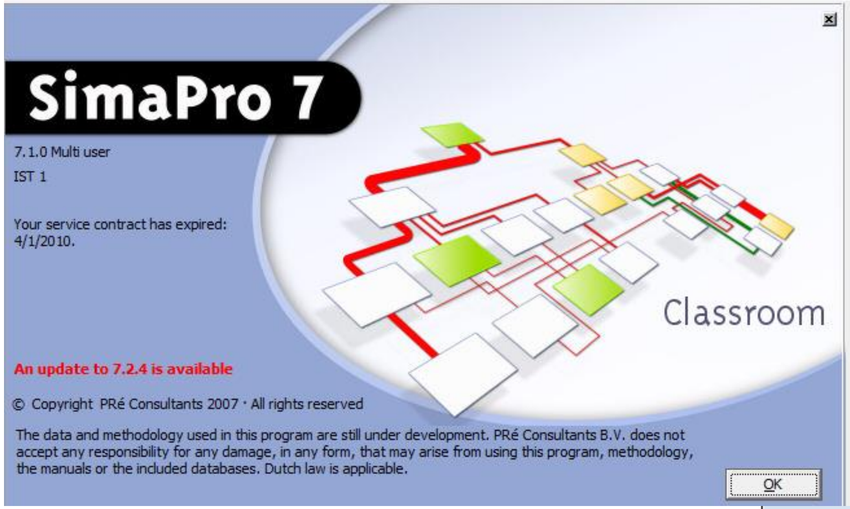
Product E-of-L	Reuse (%*)	Recycling (%*)	Landfill (%*)	Incineration (%*)
1 glass bottle reusable	70	10	20	-
1 glass bottle not "	-	40	60	-
1 plastic bottle PET	-	10	30	60

Industrial Ecology

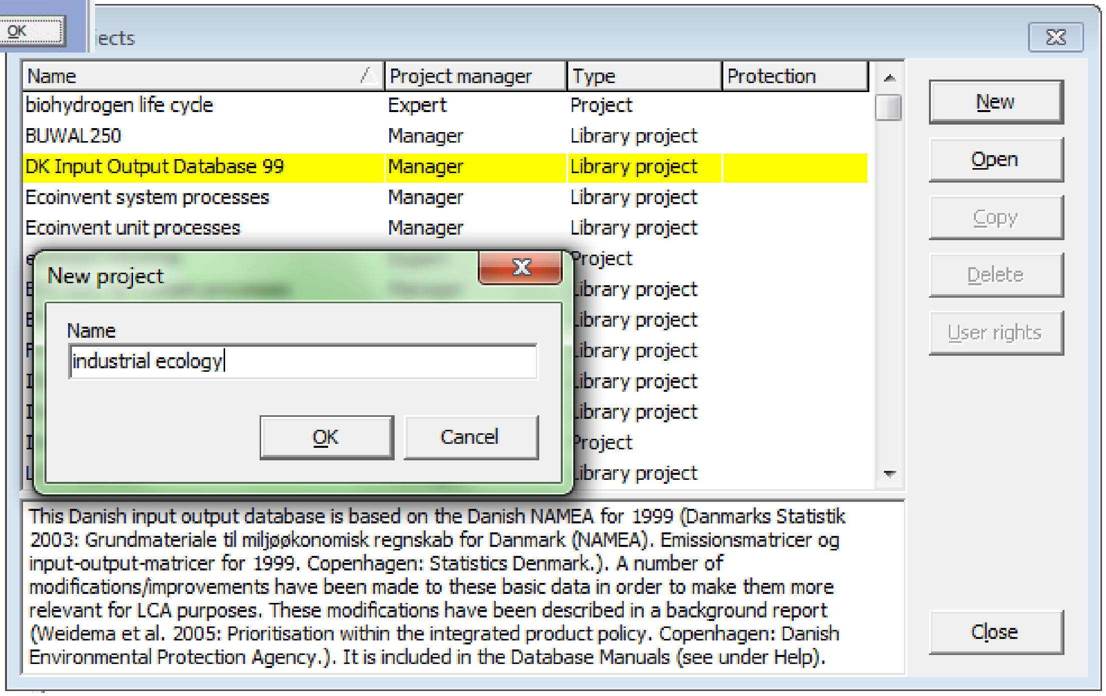


eco-point = 1/1000th of an average European's yearly environmental load

Industrial Ecology



Create a new project

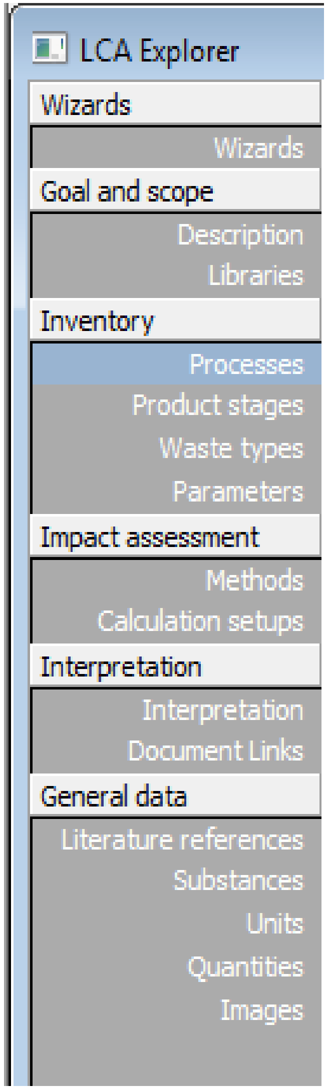


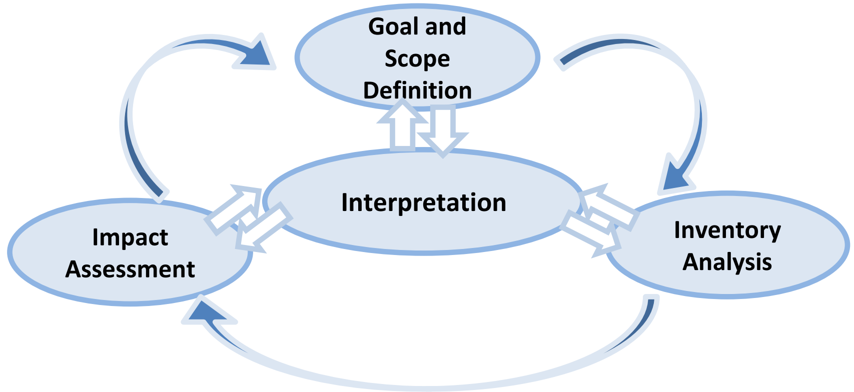
Choose New Project and give your project a name. “Industrial ecology”

Ok

Double click in project created

Industrial Ecology





Goal and Scope

The product or service to be assessed is defined, a functional basis for comparison is chosen and the required level of detail is defined.

Inventory

Analysis of extractions and emissions. An inventory list of all the inputs and ouputs of a product or service.

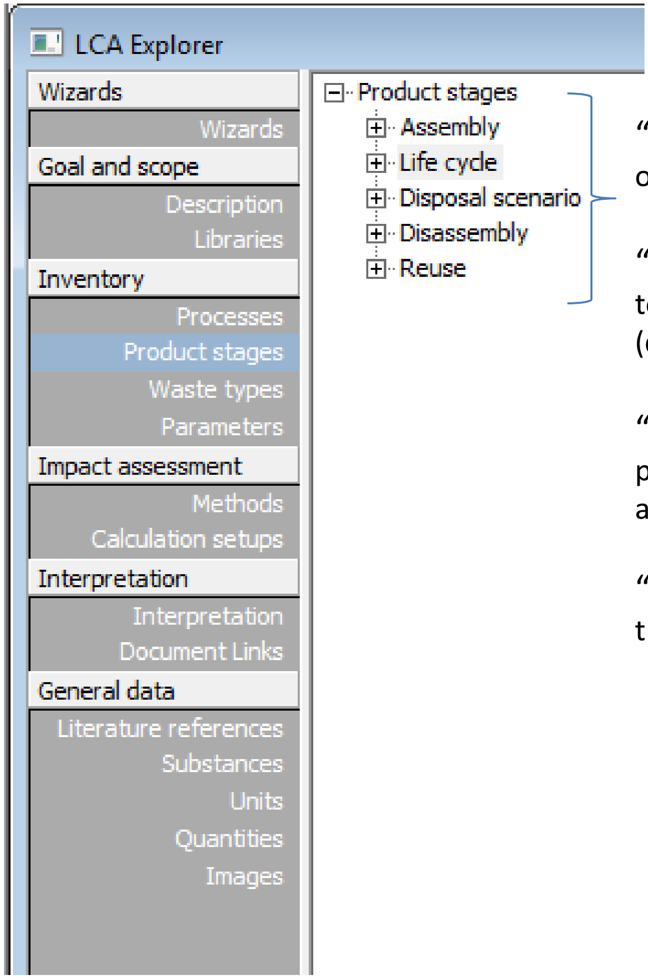
Impact assessment

The effects of the resource use and emissions generated are grouped and quantified into a limited number of impact categories which may then be weighted for importance.

Interpretation

The results are reported in the most informative way possible and the need and opportunities to reduce the impact of the product(s) or service(s) on the environment are systematically evaluated.

Industrial Ecology



“Assembly” – is a way of describing the manufacture, distribution and use of any product or service to be analyzed, which is composed of others "assemblies" and processes

“Waste /Disposal scenario” – The situation of final treatment describes the operations to which the product will be subjected after use. Thus includes screening processes (disassembly), reuse and recycling.

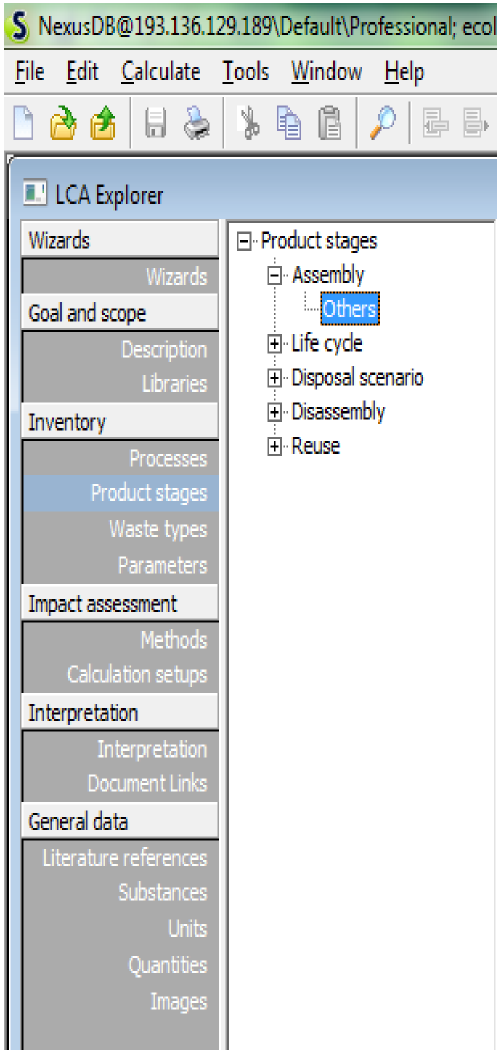
“Life cycle” – The situation of final treatment describes the operations to which the product will be subjected after use. Thus includes screening processes (disassembly), reuse and recycling.

“Reuse” - This item is intended for cases where the product in question can be reused at the end of its useful life, eg. glass bottles with return.

Industrial Ecology

Characterized impact categories are called mid-points.

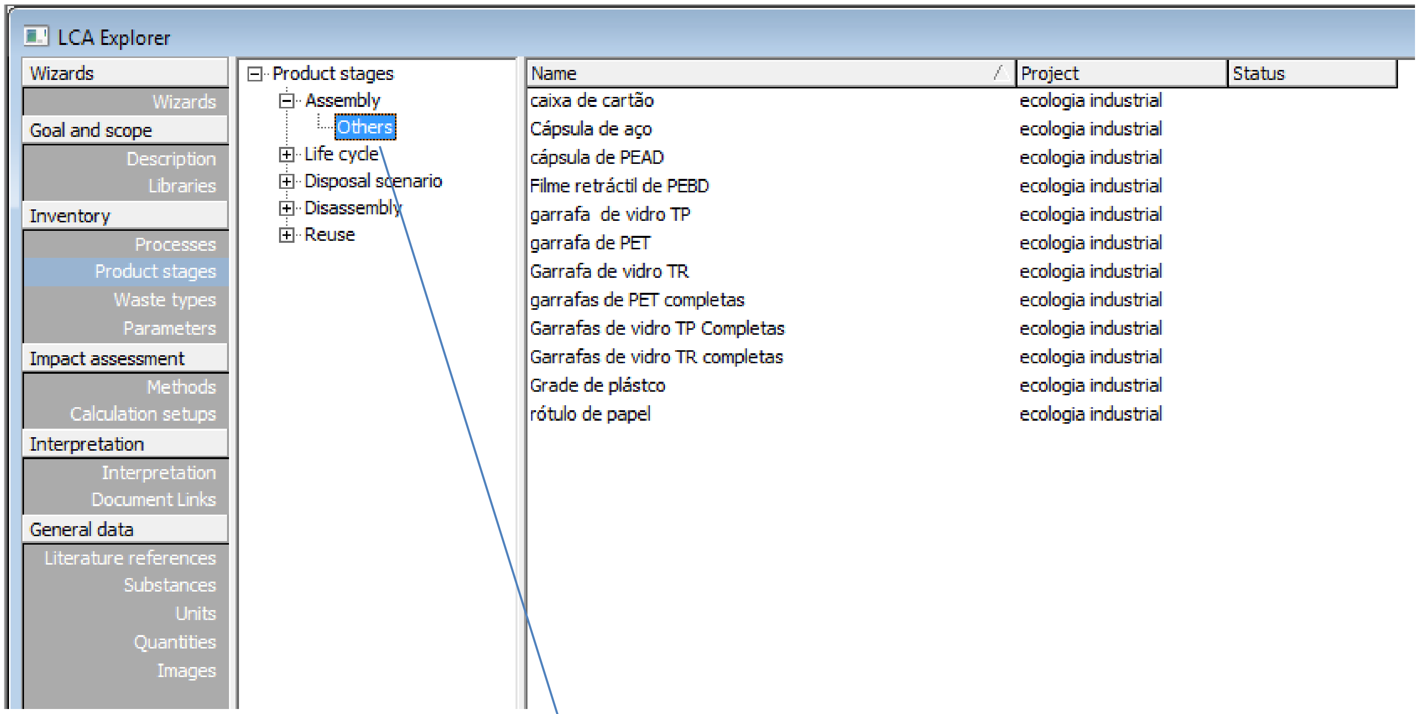
Industrial Ecology



There are 5 different categories available in the category section:

- ***Assembly***
- ***Life cycle***
- ***Disposal Scenarios***
- ***Disassembly***
- ***Reuse***

First we are going to focus on the key product stage called Assembly



1st create the Products 'Assembly'

Assembly

Others

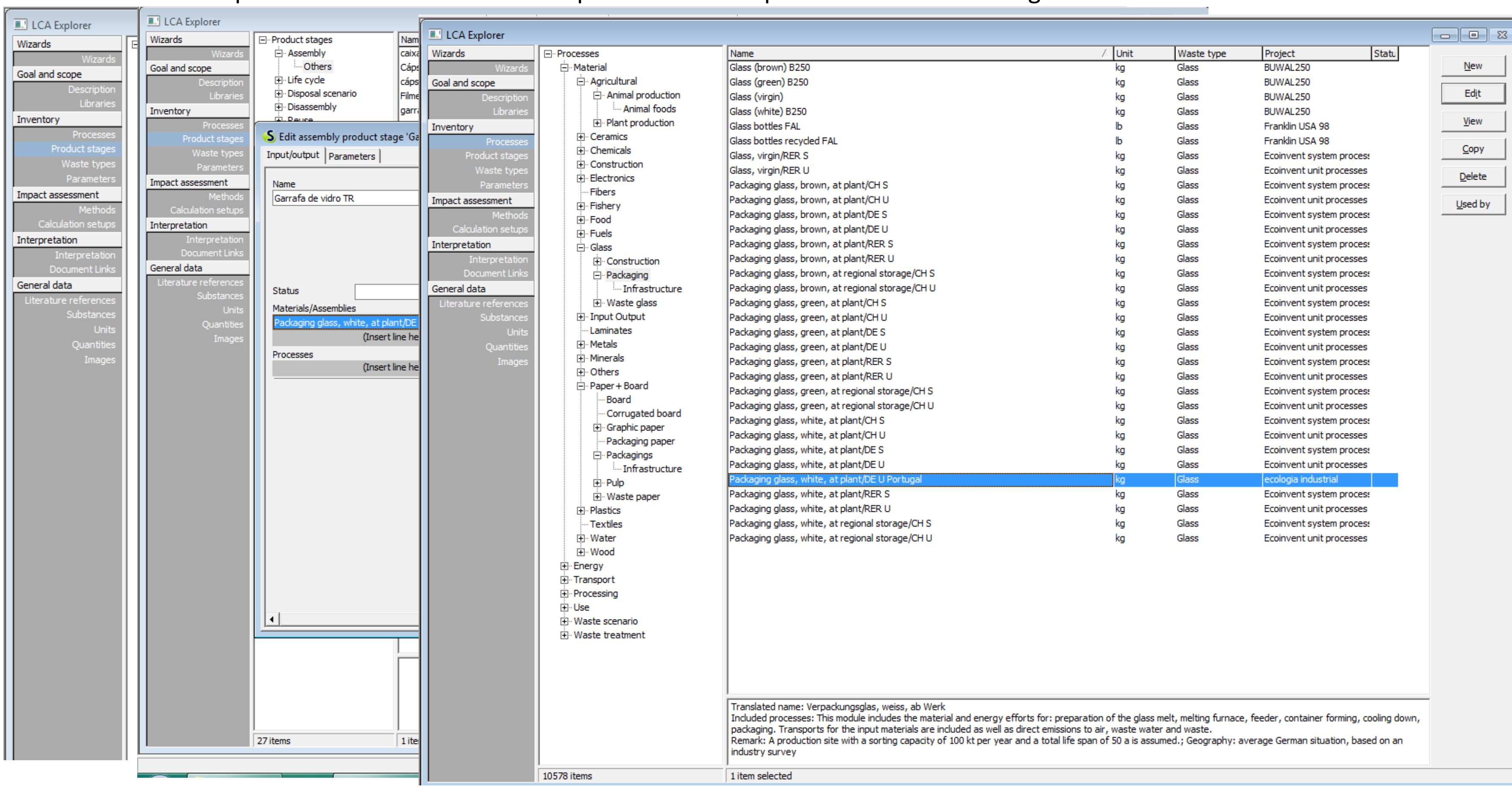
New

Industrial Ecology

Double click:
Write a name of product

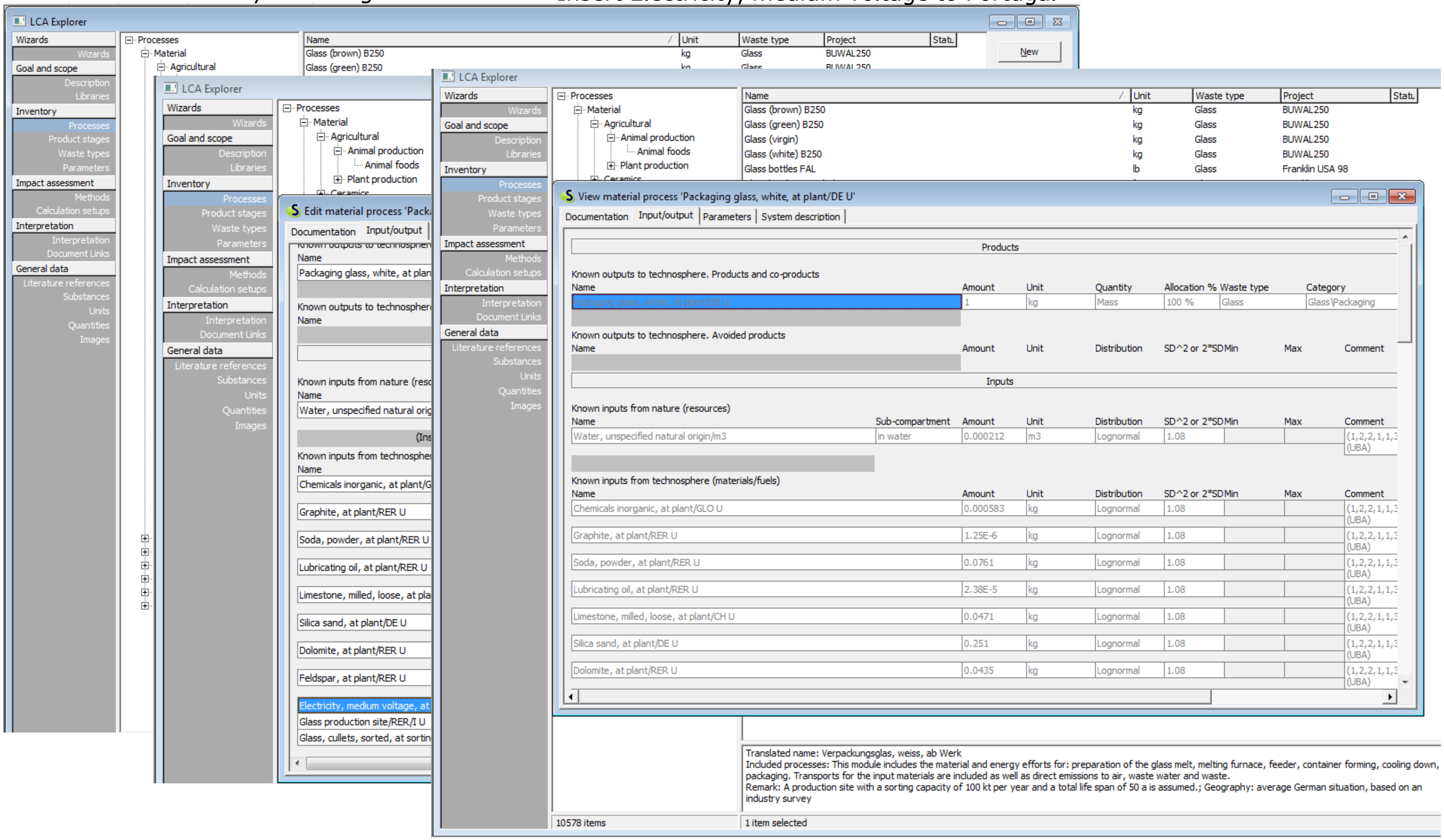
Double click:
Select the adequate material in processes

In amount: double click and insert the product weight and the associated unit



Industrial Ecology

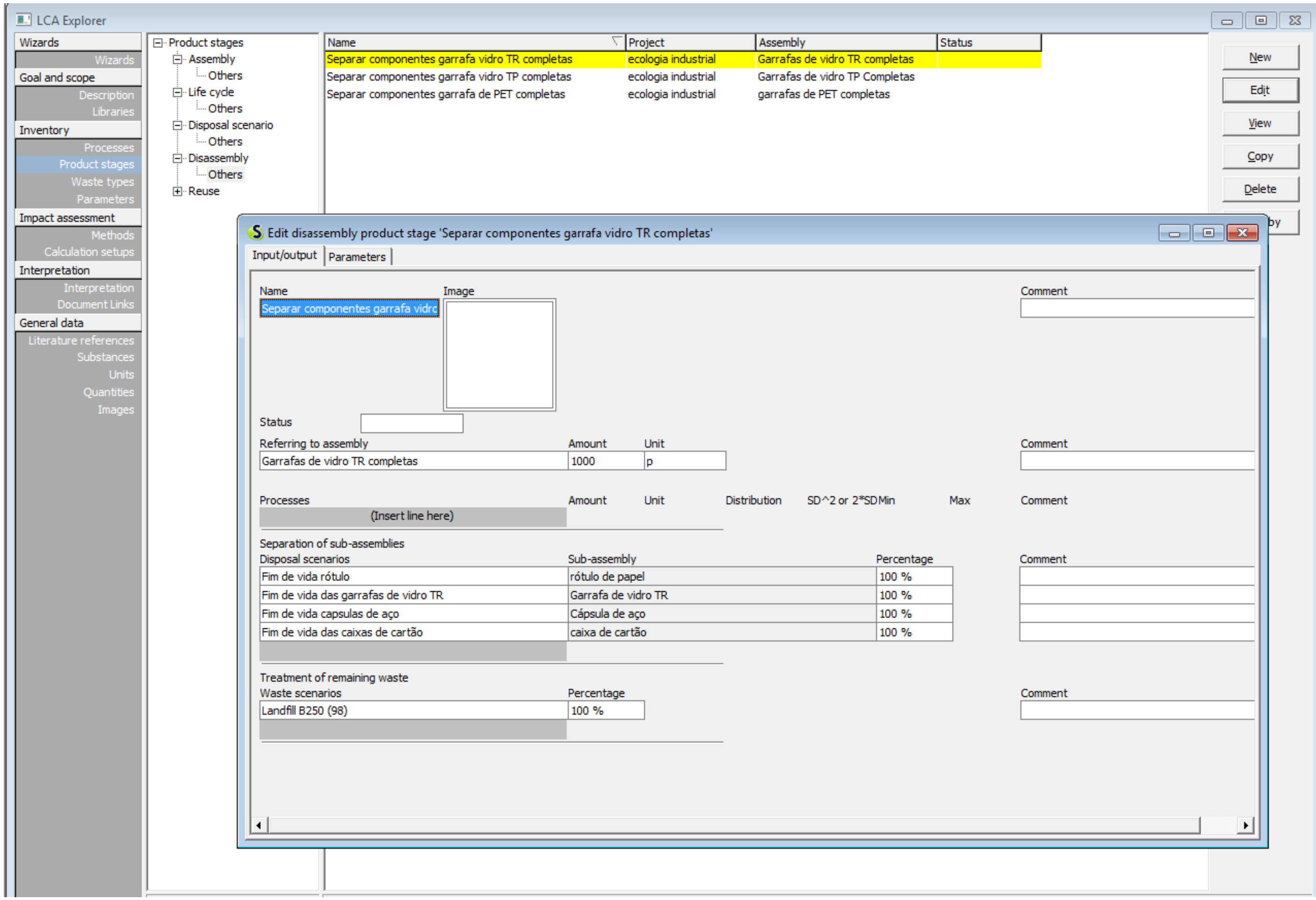
Convert all electricity to Portugal case Insert Electricity, medium voltage to Portugal



Industrial Ecology

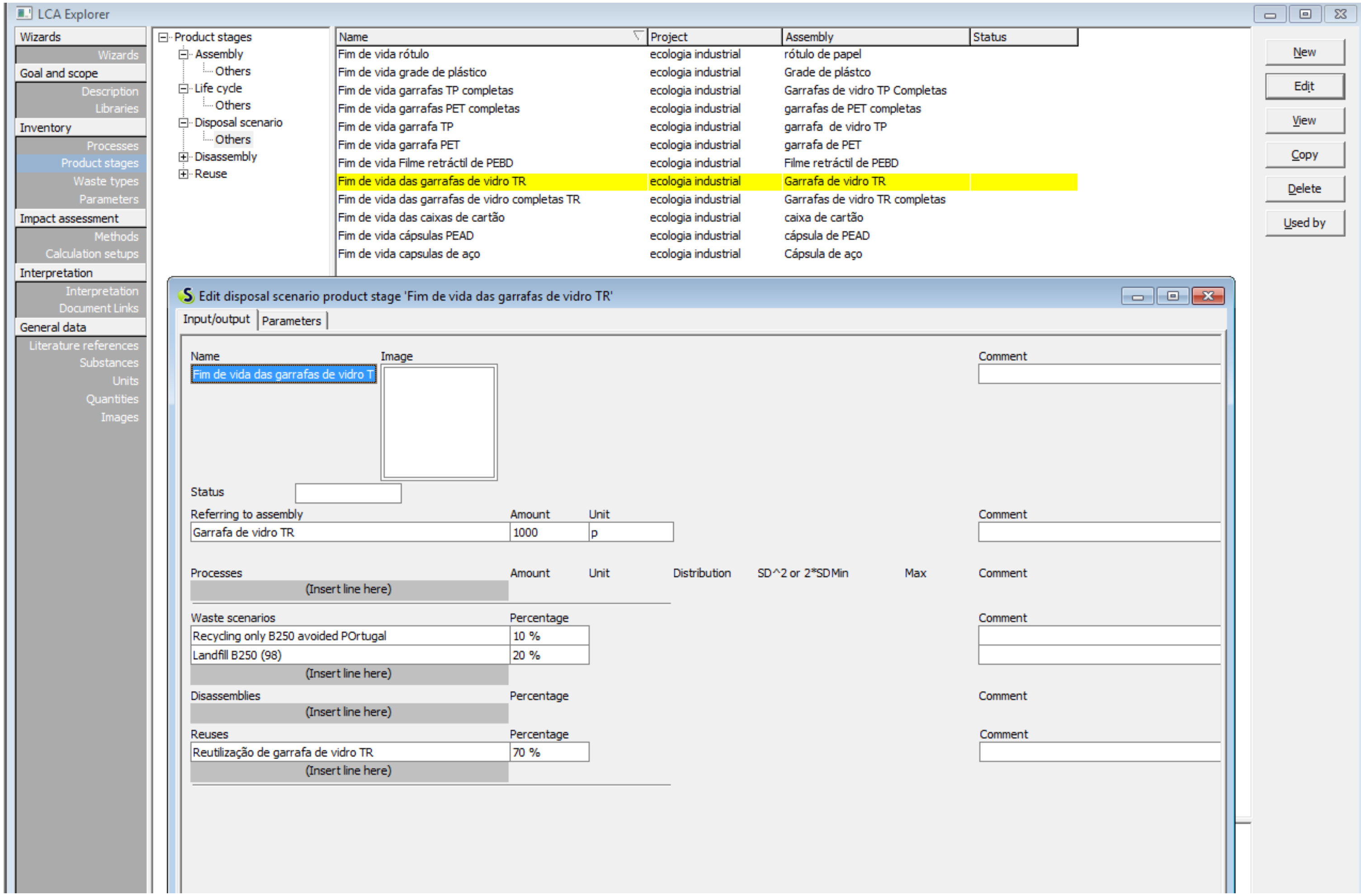
In Disassembly:

Create the component separation for each complete bottle

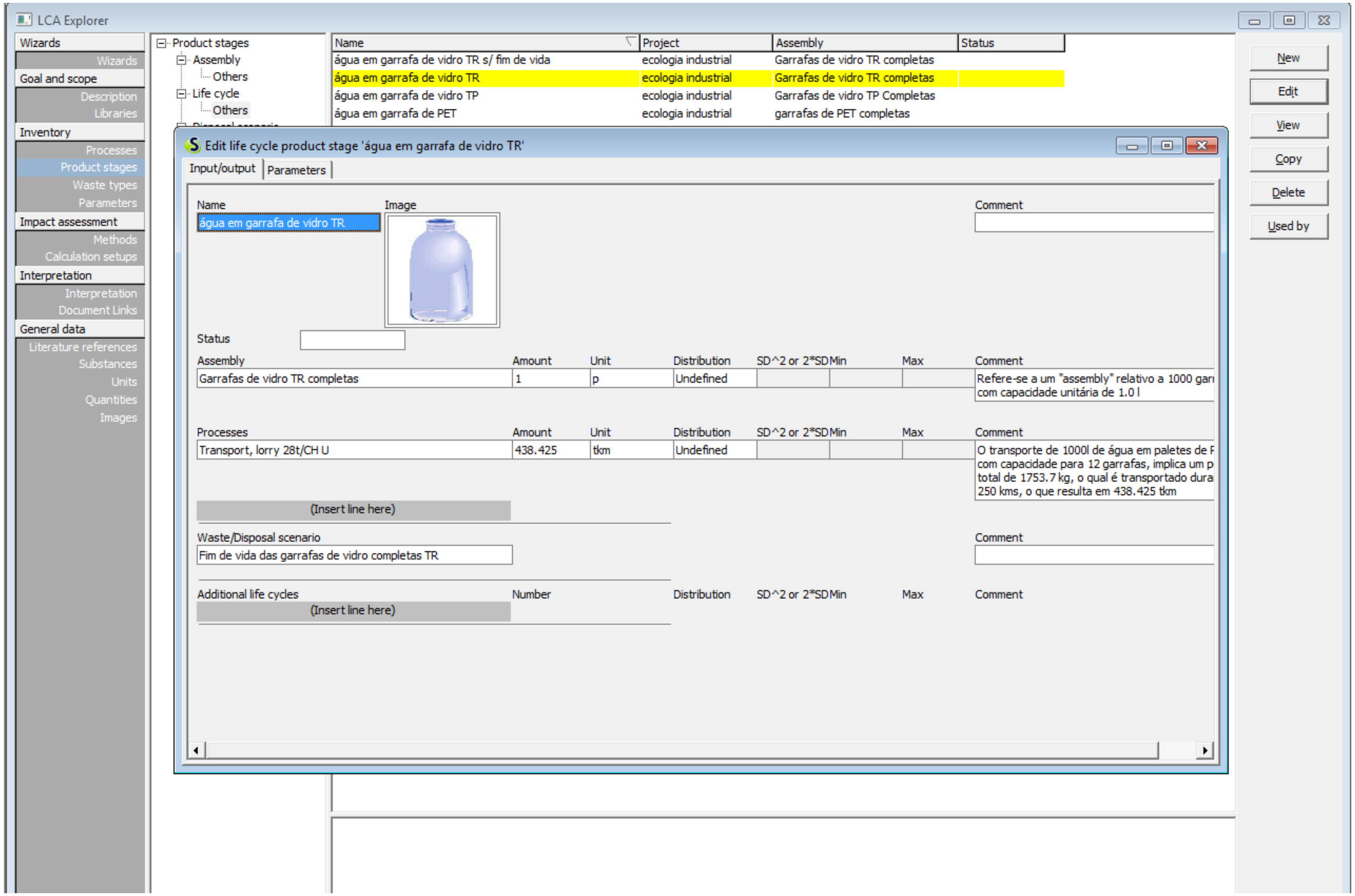


Industrial Ecology

In Disposal scenario:
Create the end product life for each product created



Finally create a life cycle considering:
- Complete Glass bottle TR or PT or complete PET bottle;
- Transport;
- End of life of Complete Glass bottle TR or TP or complete PET bottle

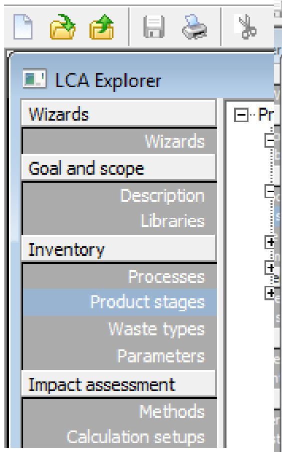


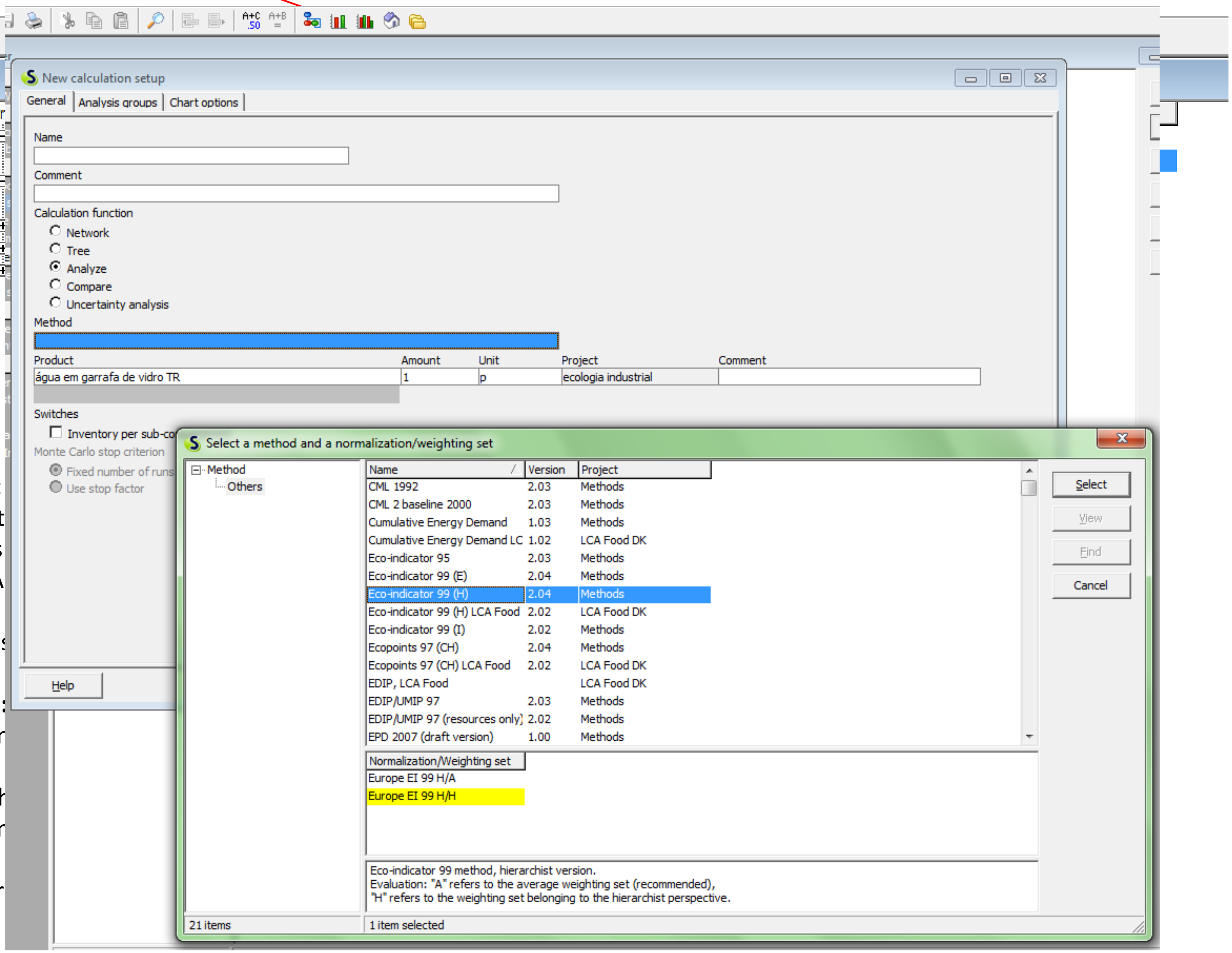
E-mail: carla.silva@ist.utl.pt

Industrial Ecology

Analyze

Choose appropriate method





Life cycle impact
The inventory list
list of substances
assessment (LCIA

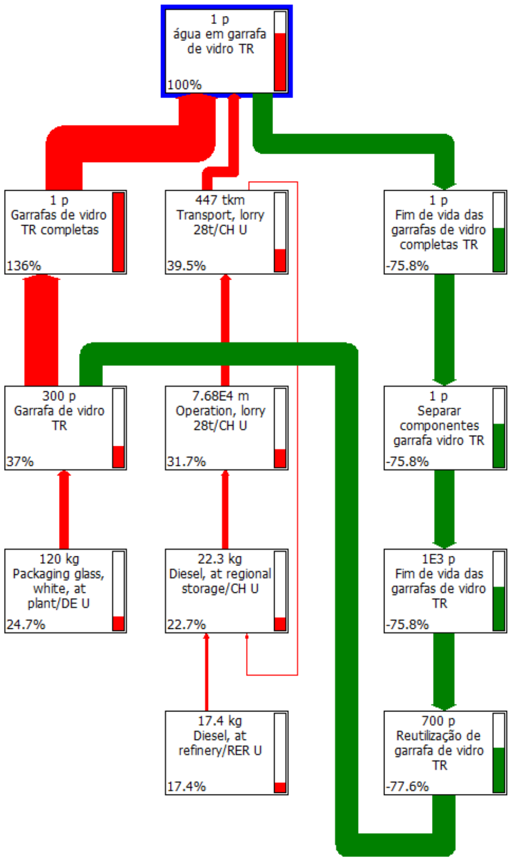
Classifcation: all s

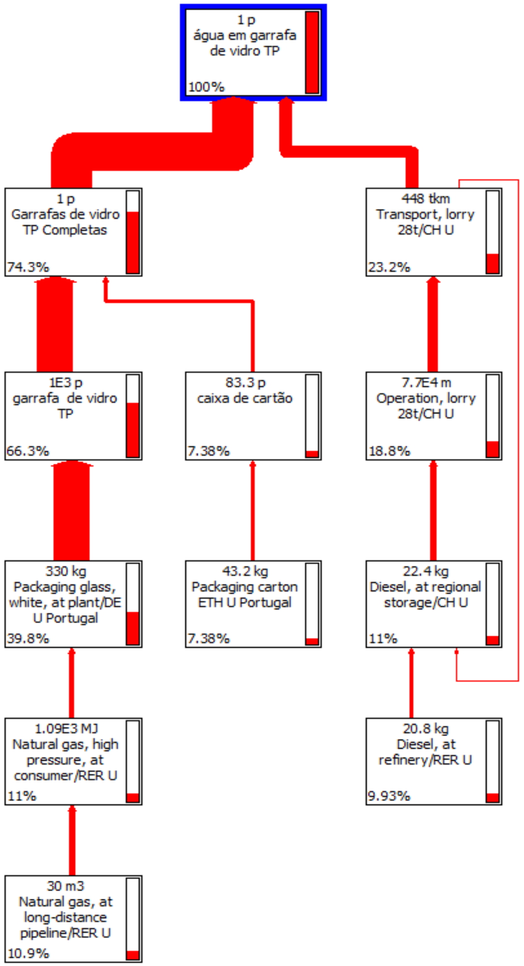
Characterisation:
environmental im

Normalisation: th
environmental im

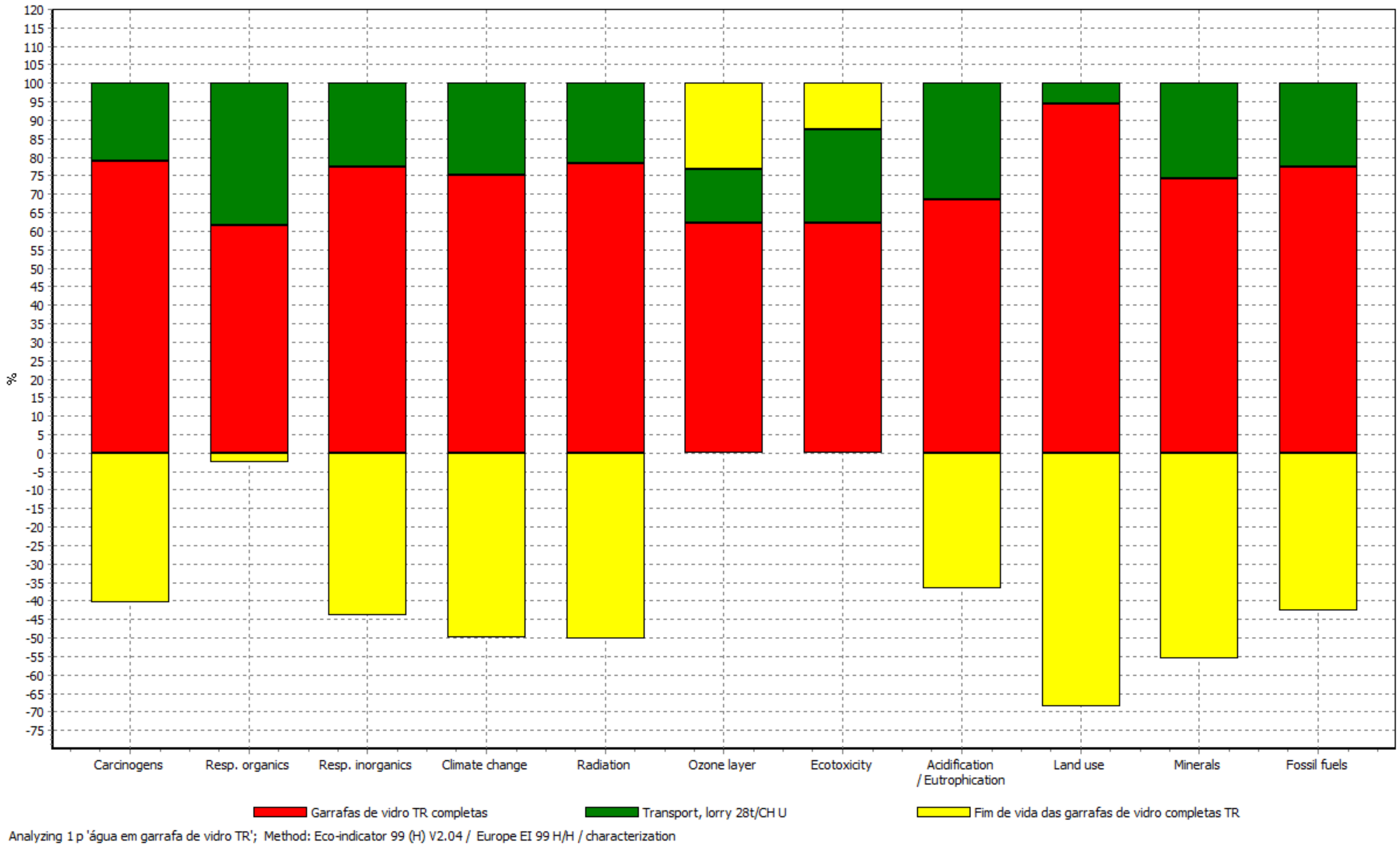
Weighting: differ

Network: Scheme of life cycle





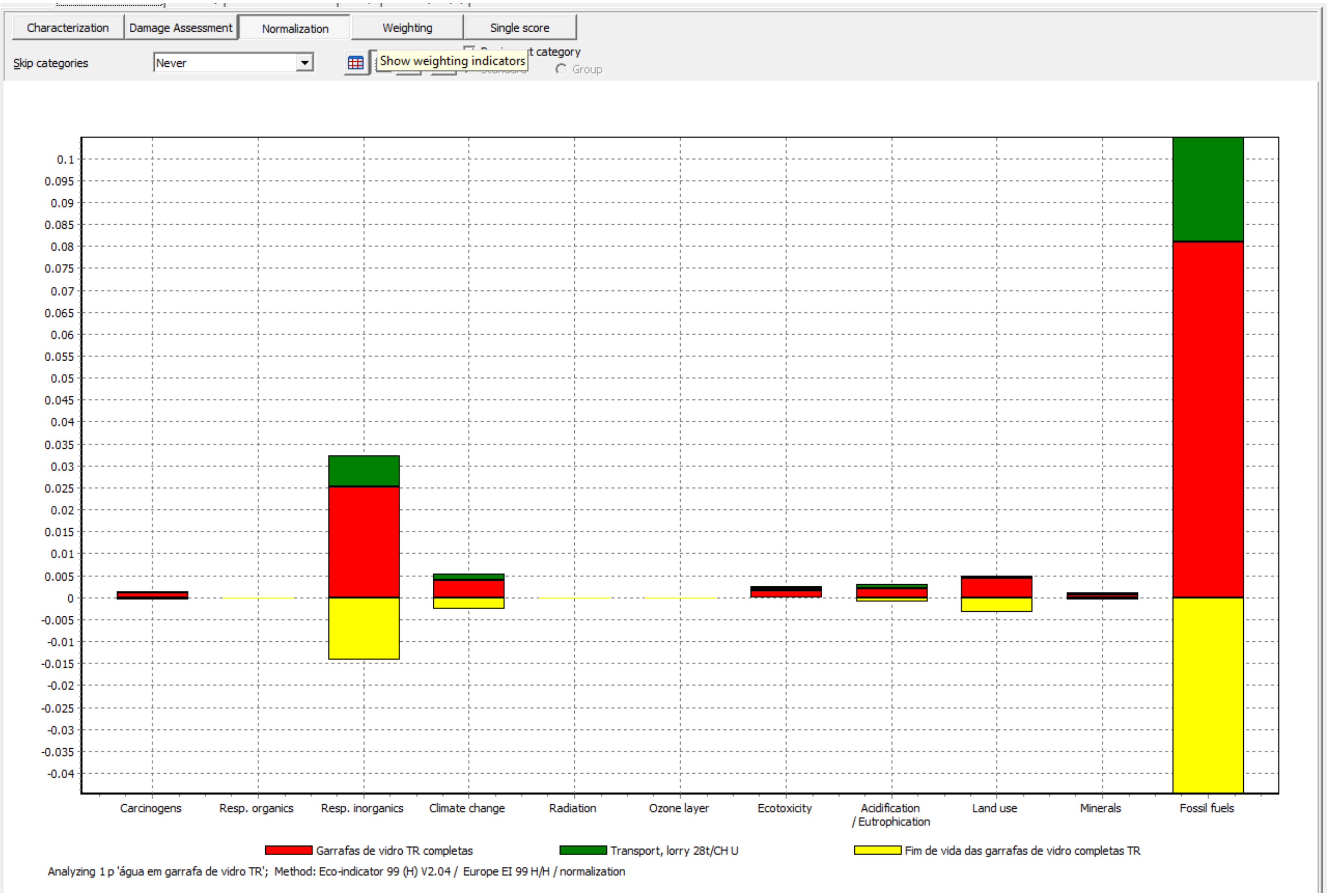
Industrial Ecology



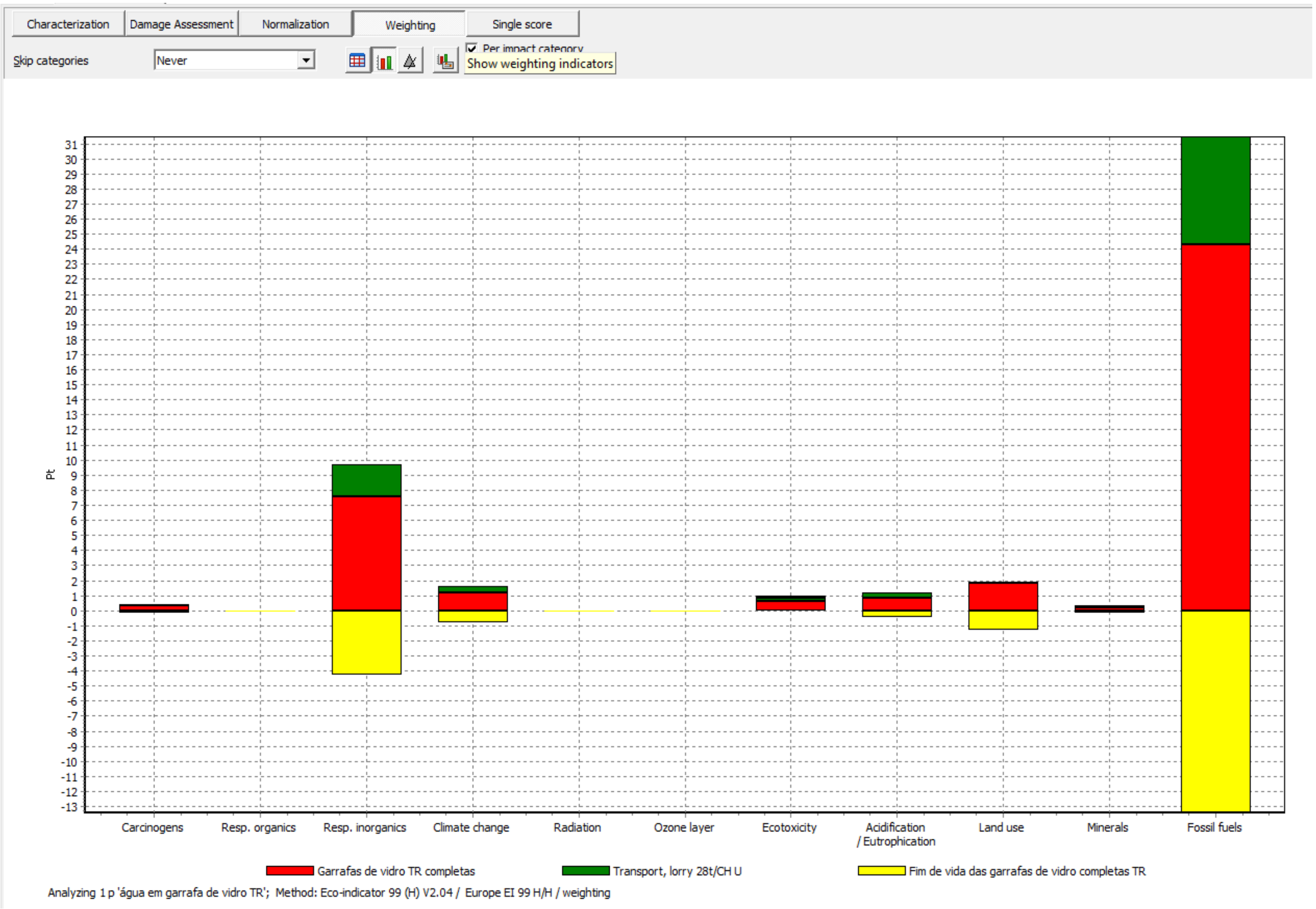
Method:
Eco-indicator 99

Method:
Eco-indicator 95

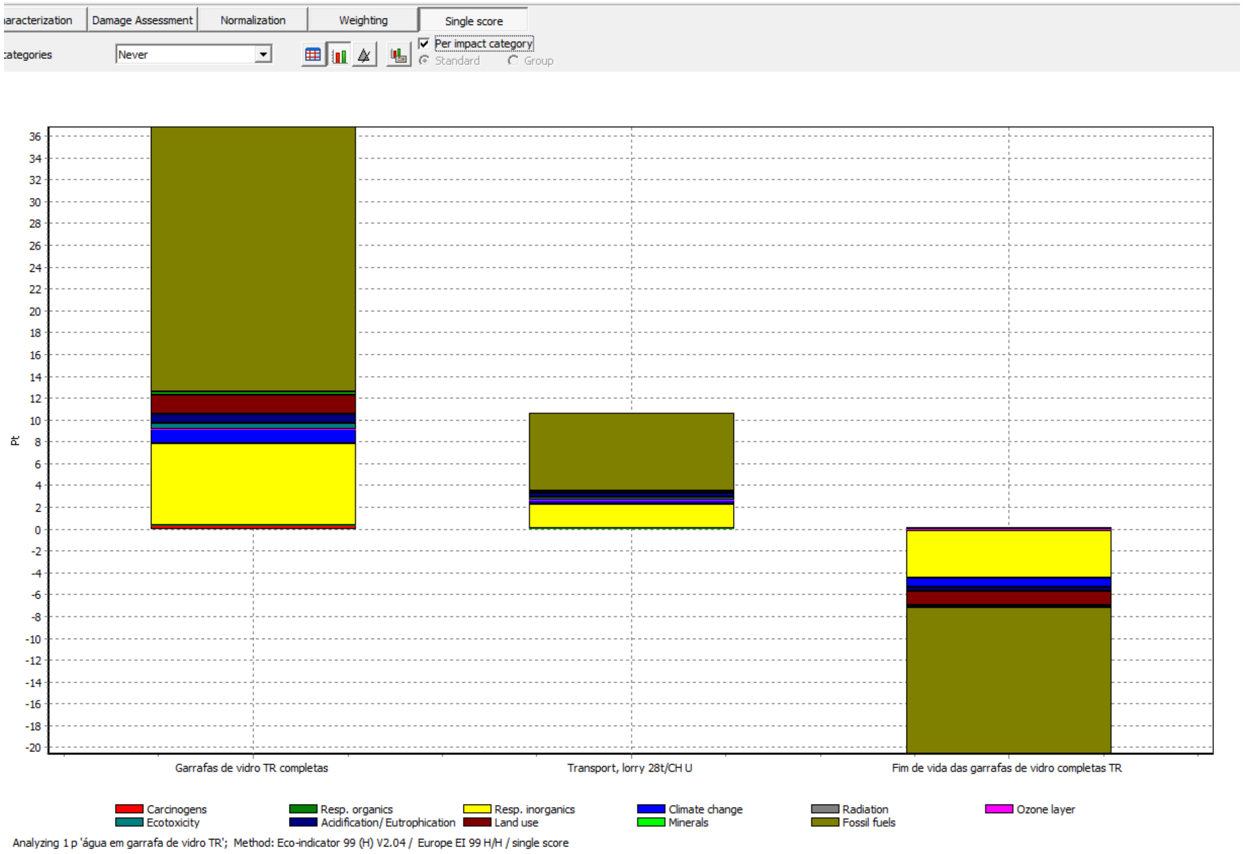
Industrial Ecology



Industrial Ecology



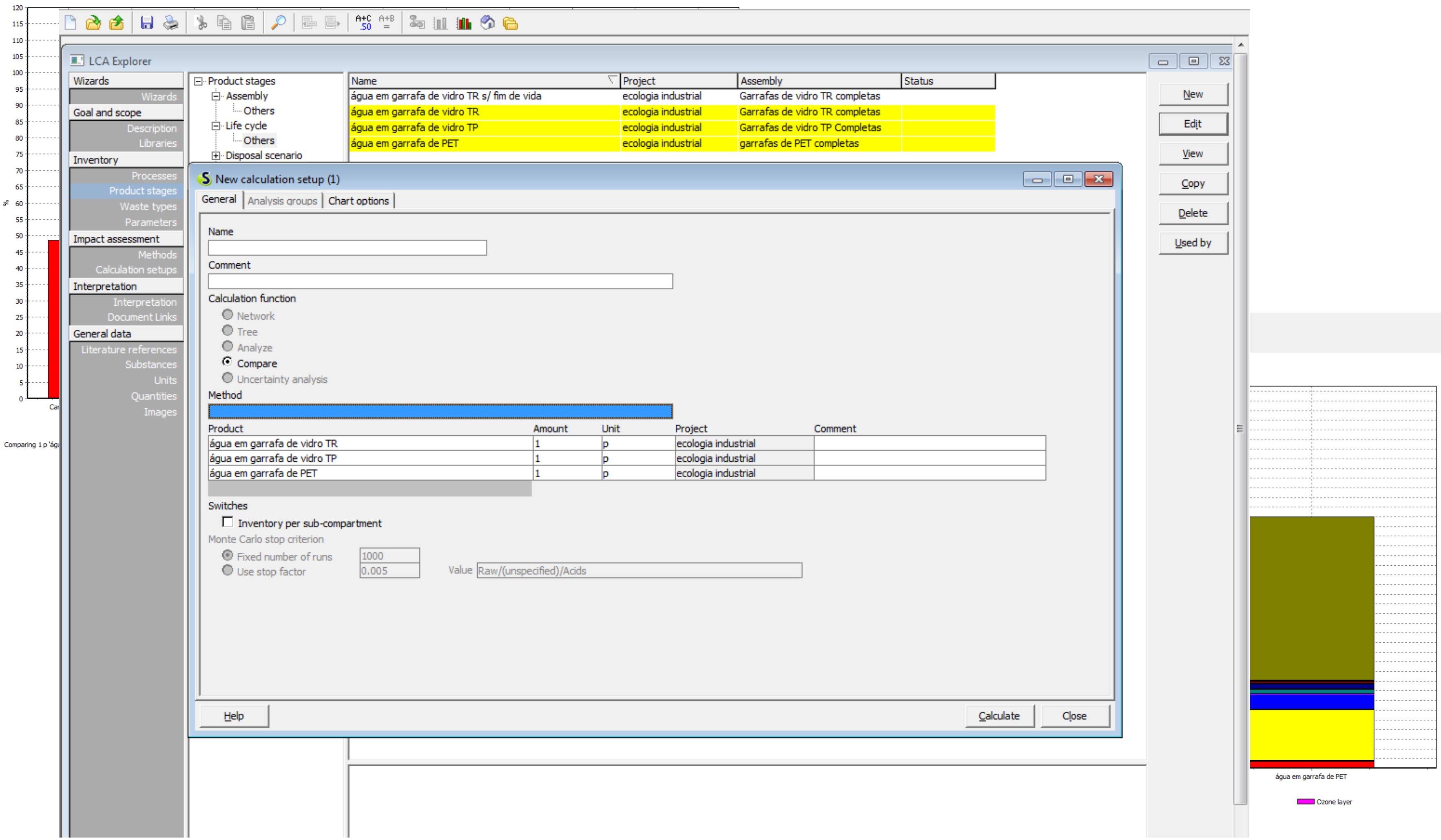
Industrial Ecology



Industrial Ecology

Industrial Ecology

Comparative analysis



Life Cycle based studies

Bottle	• Exercice Simapro
Biofuel	• LCI Energy & CO_2/ WTW
Aluminum packadge	• LCA midle point

 E-mail: carla.silva@ist.utl.pt

Biofuel { • LCI Energy & CO_2/ WTW

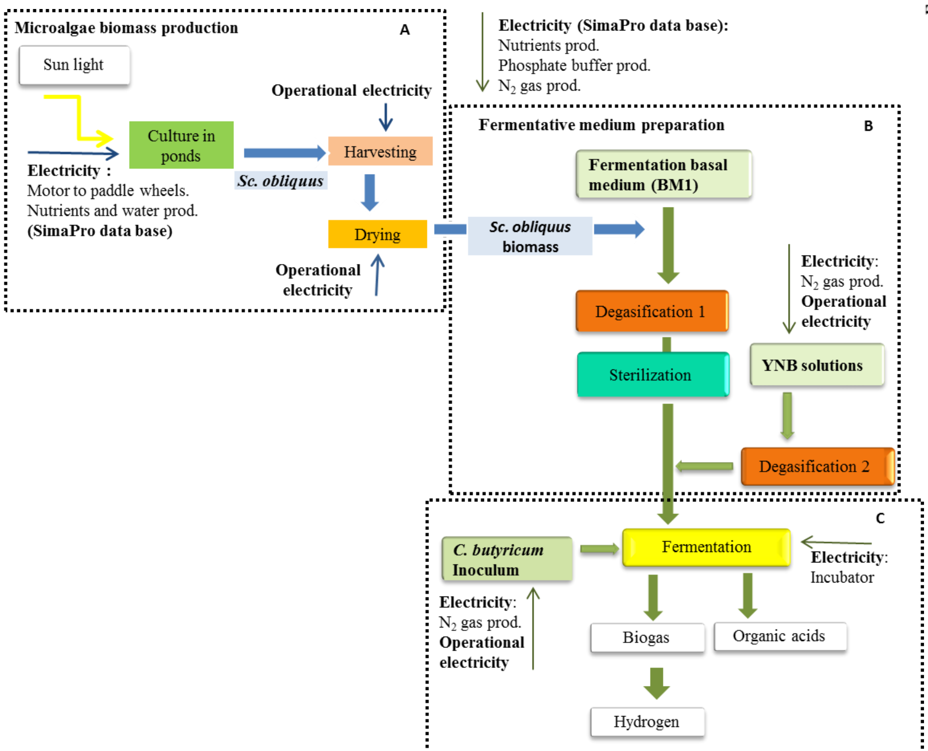
algal/H_2 production

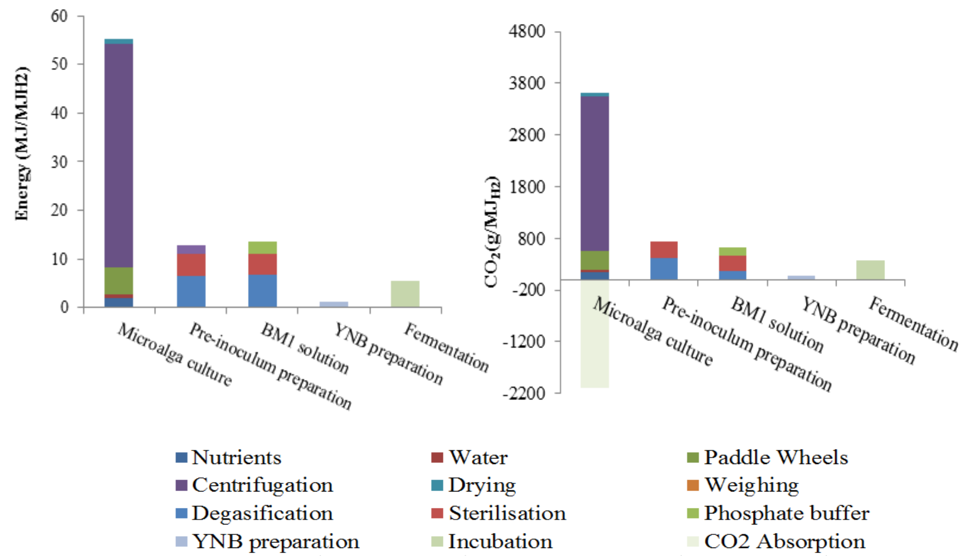
Fuel cell road vehicles

 E-mail: carla.silva@ist.utl.pt

Industrial Ecology

Scenedesmus obliquus microalgae





- BioH_2 production yield: 7.3 $g_{H2}/kg_{biomass}$.
- The use of open raceway ponds show a reduction of 10 orders of magnitude than the ones of the works referred above.
- Microalga culture accounted only for 62% of the global energy consumption.
- Considering CO_2 absorption, values of CO_2 emissions decrease 36.1%

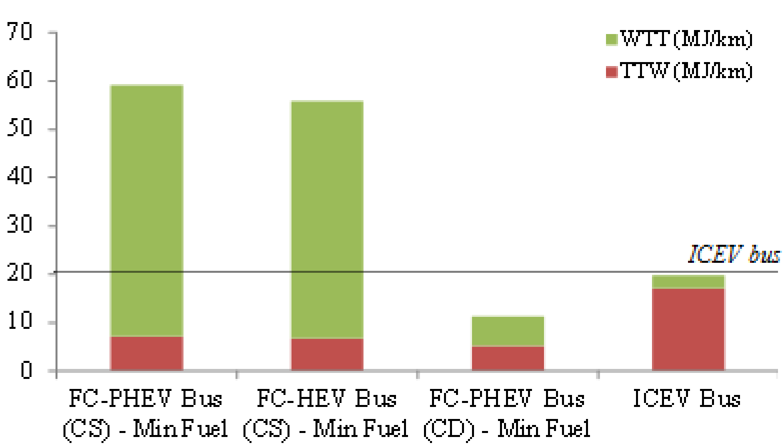
H_2

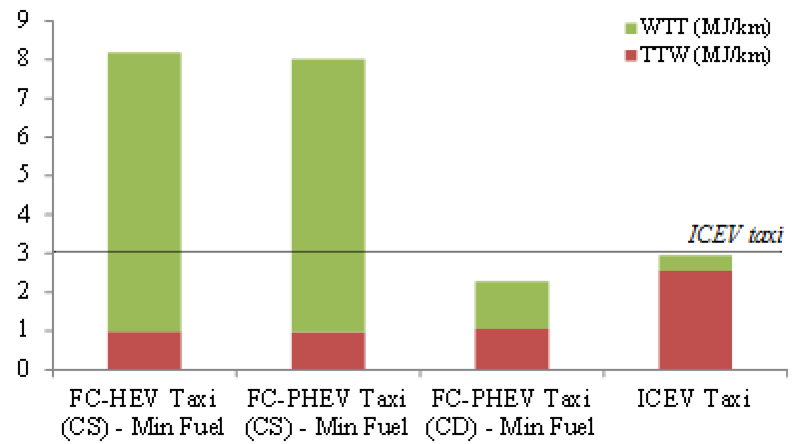
Cradle-to-Gate results

BioH_2 chain	Algae sugar content DW	Energy (MJ/MJ_{H2})	Min	Max	CO_2 (g/MJ_{H2})	Min	Max
BioH_2 from dried *Sc. obliquus* **- best scenario**	30 %	7.20	5.72	8.23	-659	-716	-613
BioH_2 from dried *Sc. obliquus* **- optimized scenario**	30%	12.48	9.80	14.60	-311	-419	-209
BioH_2 as by-product from dried *Sc. obliquus*		33.28	27.28	37.26	2172.0	1935.1	2331.6
BioH_2 from dried *Sc. obliquus*	30%	88.00	70.31	99.49	5776.0	5118.4	6268.0
BioH_2 as by-product from bioref 1 *Nannochloropsis* **sp.**		147.00	119.00	164.00	9665.0	8645.0	10369.0
BioH_2 as by-product from bioref 2 *Nannochloropsis* **sp.**		168.00	136.00	187.00	11020.0	9858.0	11820.0
BioH_2 as by-product from *Sc. Obliquus* **hydrolyzate**		364.30	281.20	404.90	27198.0	24149.0	29218.0
BioH_2 by *Anabaena* **sp. (Photoautotrophic)**	25-30%	1538.00	1184.00	1715.00	114641.0	101476.0	123587.0
BioH_2 by *Anabaena* **sp. cyanobacteria (Photoauto.+Ferm.)**	25-30%	1723.00	1327.00	1919.00	128502.0	113825.0	266887.0
BioH_2 from *Sc. obliquus* **hydrolyzate**	10-17%	8884.14	7614.14	9866.14	758743.8	673892.4	813576.4
BioH_2 from *Nannochloropsis* **sp.**	17%	9058.00	7285.00	10123.00	591112.0	527022.0	634402.0

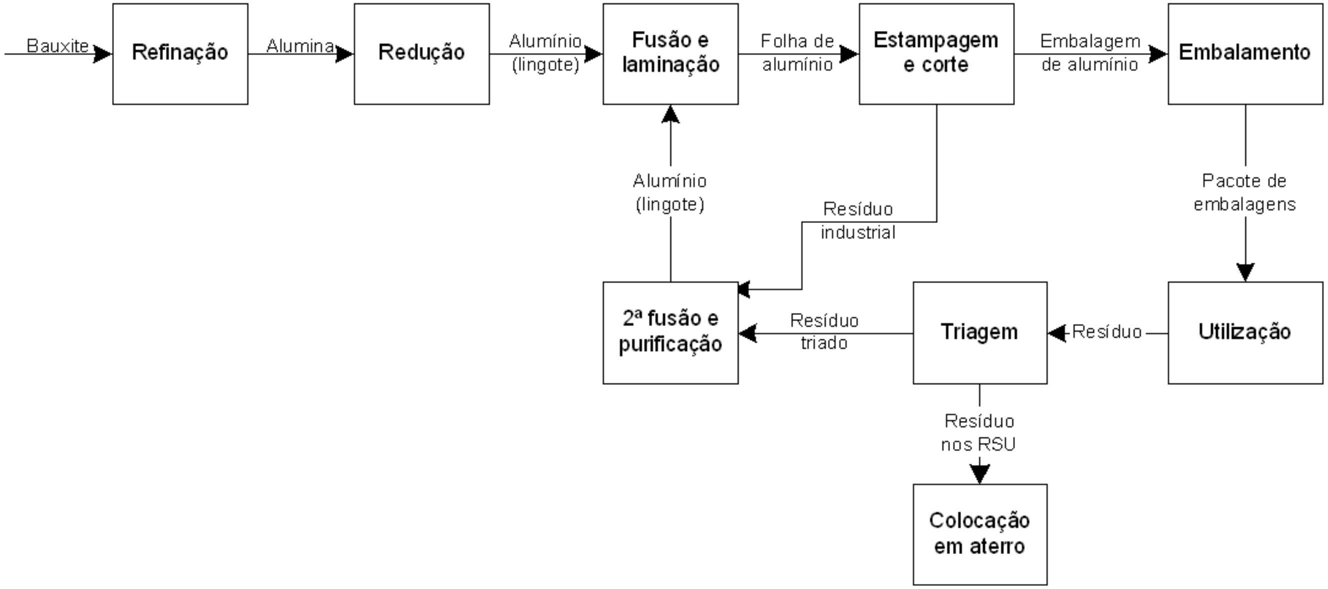
E-mail: carla.silva@ist.utl.pt

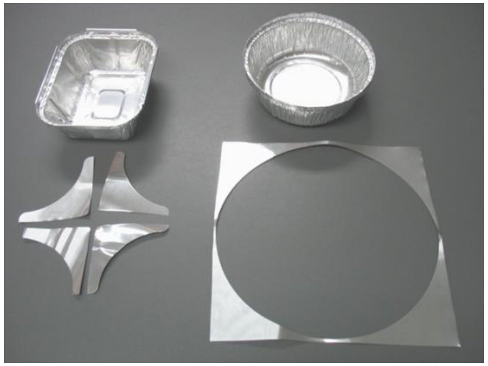

Scenedesmus obliquus
microalgae – Best scenario


70
60
50
40
30
20
10
0
WTT (MJ/km)
TTW (MJ/km)
ICEV bus
FC-PHEV Bus (CS) - Min Fuel
FC-HEV Bus (CS) - Min Fuel
FC-PHEV Bus (CD) - Min Fuel
ICEV Bus


9
8
7
6
5
4
3
2
1
0
WTT (MJ/km)
TTW (MJ/km)
ICEV taxi
FC-HEV Taxi (CS) - Min Fuel
FC-PHEV Taxi (CS) - Min Fuel
FC-PHEV Taxi (CD) - Min Fuel
ICEV Taxi

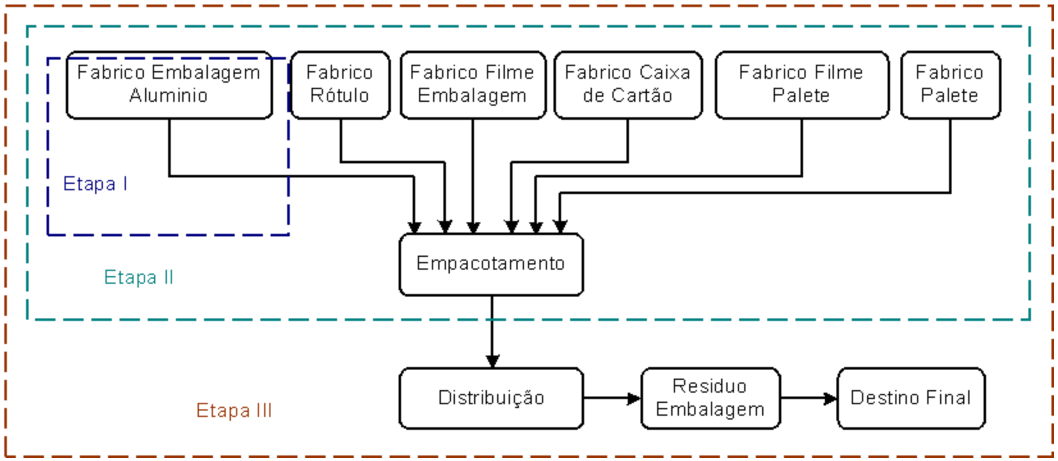
Lusoforma vs ideal





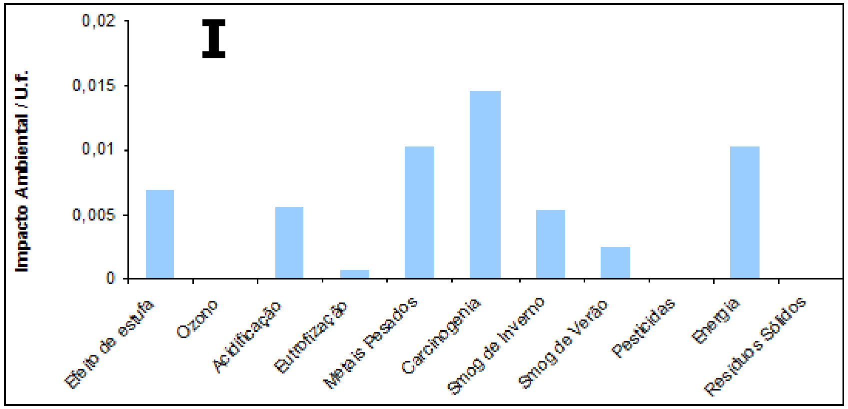
Comparing: Real vs. Ideal with volume 1 litre and tickness 0.07mm

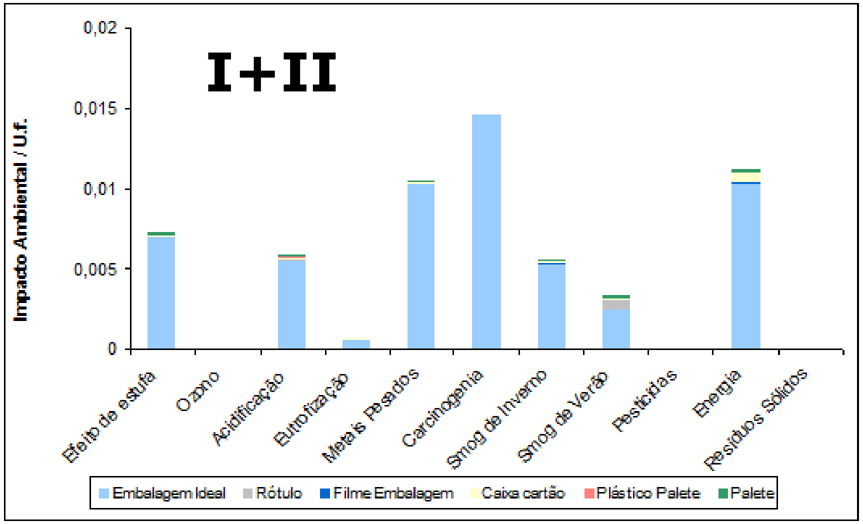
FU: 1000 packages 1 litre



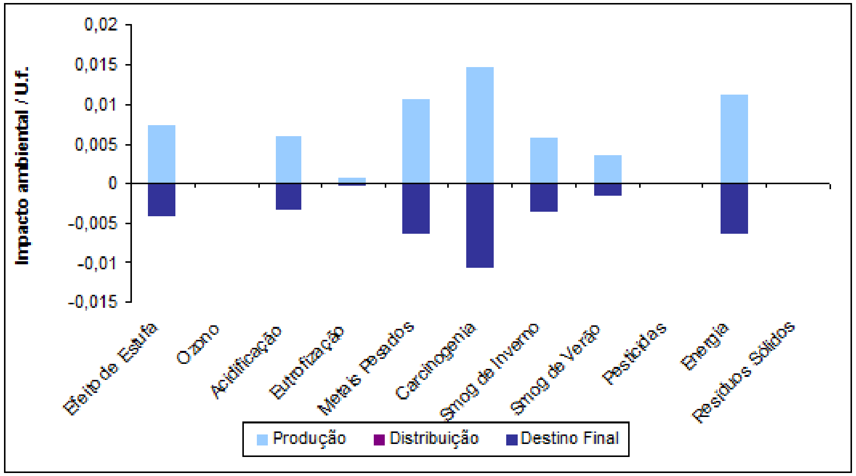
Etapa I - a produção da embalagem de alumínio (inclui os valores relativos às etapas de processamento da matéria-prima);
Etapa II - o produto embalado, considerando todos os materiais de empacotamento;
Etapa III - todo o ciclo de vida da embalagem, incluindo as fases de produção, distribuição e destino final.

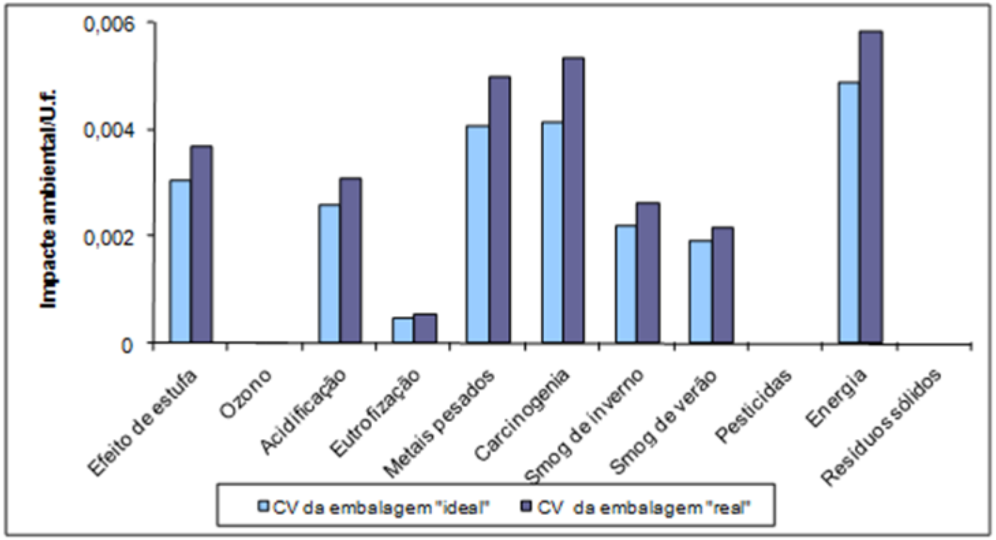
Industrial Ecology





I+II+III





0,006
0,004
0,002
0
Impacte ambiental/U.f.
Efeito de estufa
Ozono
Acidificação
Eutrofização
Metais pesados
Carcinogenia
Smog de inverno
Smog de verão
Pesticidas
Energia
Resíduos sólidos
CV da embalagem "ideal"
CV da embalagem "real"

Exercises (Functional Unit)

Problem setting ➡ System ➡ Base for comparisons:

What is the function of the system?

Transport passengers valid FU p*km

Exercises (Functional Unit)

What is the function of the system?

Transport merchandise valid FU ton*km

Provide water valid FU 1000 l water provided

Exercises (Functional Unit)

Provide washes valid FU 50 showers or 100 g of soap used

one-way or rechargeable batteries

Provide energy to the remote control valid FU ?

Exercises (Functional Unit)

Provide biodiesel valid FU?

Online or conventional book

Provide info valid FU?

Exercises (alocation)

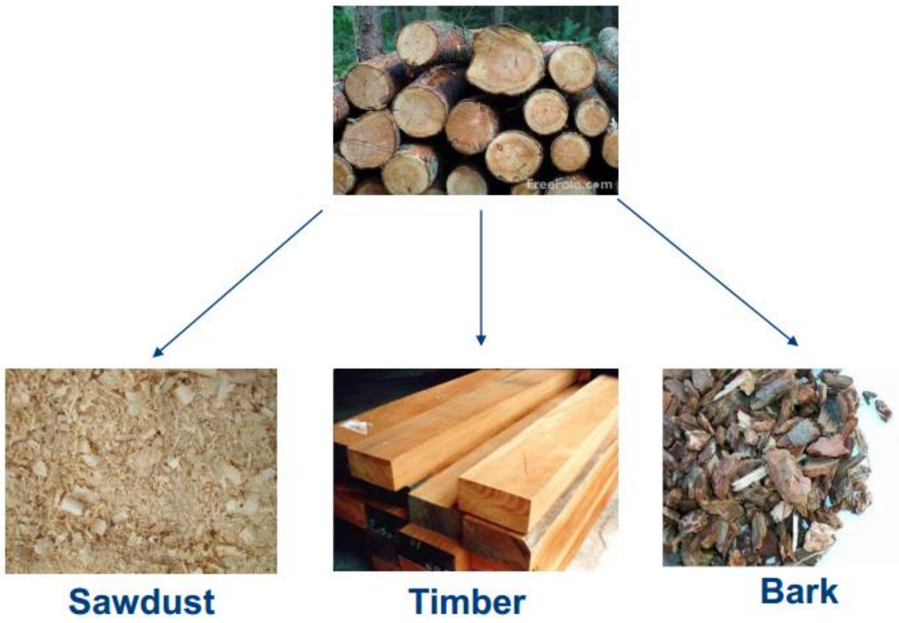
Production of a wooden shed.

The shed is built from timber which is produced from logs.

 E-mail: carla.silva@ist.utl.pt

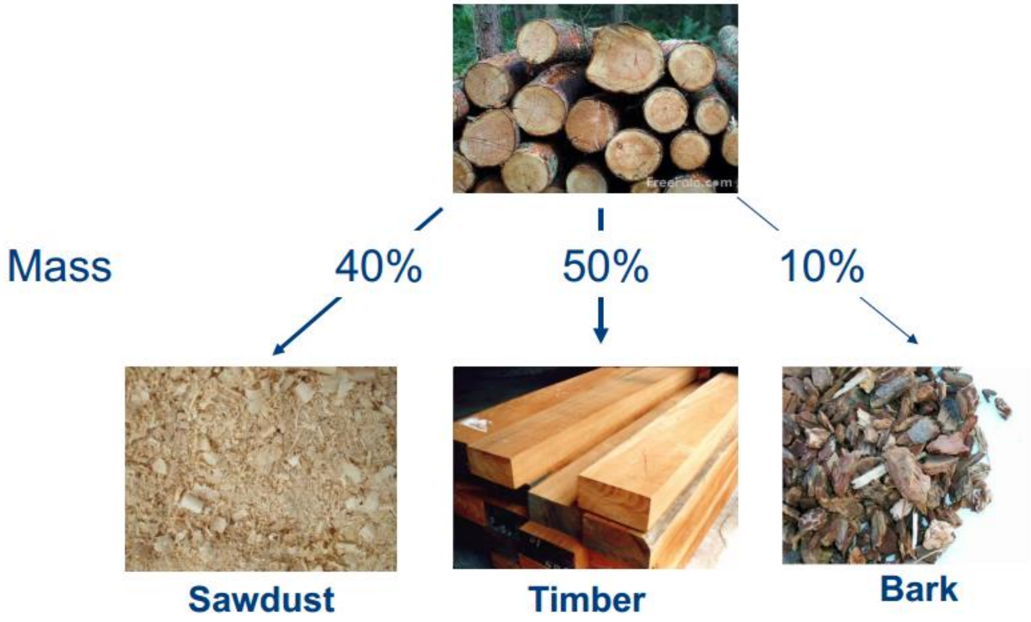
Exercises (alocation)

However, logs also produce a number of other co-products, so how much of the impact of logs do we allocate to the timber?



Exercises (alocation)

We could allocate based on the mass of each product produced by the logs?

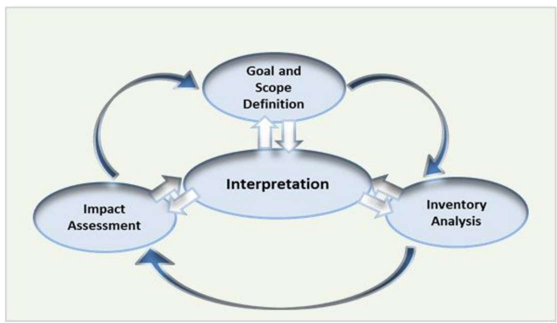


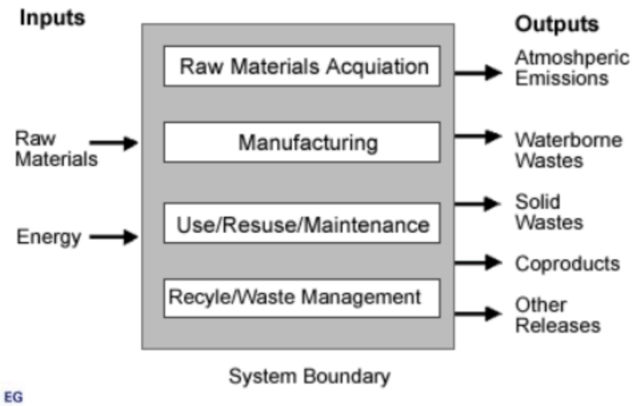
Exercises (alocation)

However, the logs are produced for economic reasons. Therefore, is it fairer to allocate impact based on the value of the products produced?

Exercises (Impact assessment)

Glass bottle

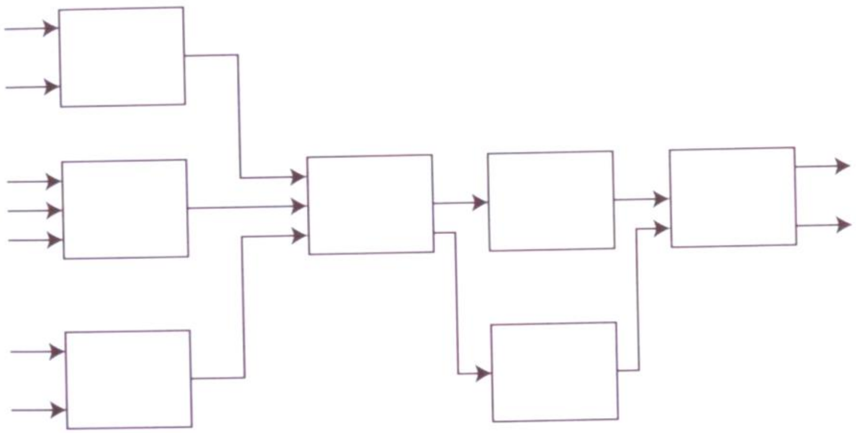




FU 1000 l of provided water

Inventory table

Exercises (Impact assessment)



Inventory Table	per FU	
CO2	915	g
CH4	1.08	g
N2O	6.37	mg
Halon-1301	53.93	microg
CO	1.74	g
NO2	4.95	g
SO2	2.86	g
NO	3.23	mg
Hydrochloric acid (HCL)	64.63	mg
HF	14.66	mg
Amonia (NH3)	34.86	mg
Ni	808.34	mg
Benzene (C6H6)	7.43	mg
Chromium (Cr)	1.8	microg
PAH	5.95	microg
Cd	12.37	microg
Pb	40.57	mg
Mn	29.62	microg
Hg	2.7	microg
Aldehydes	273.46	microg
NMVOC	2.58	g
dust	1.28	g
Cu	3.72	microg
Zn	615.49	microg
Cr	1.8	microg

Exercises (Impact assessment)

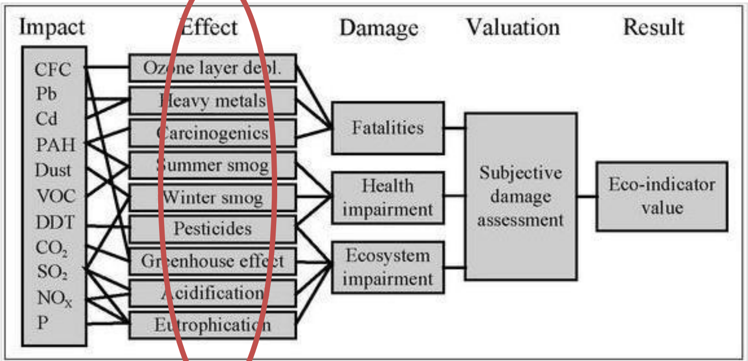
Calculate impact category, per FU:

- Global warming gCO_2 eq;
- Ozone depletion gCFC11 eq;
- Acidification gSO2 eq;
- Carcinogenic gPAH eq;
- Eutrophication gPO4 eq;
- Heavy metal g Pbeq;
- Summer smog gC2H4 eq;
- Winter smog gdust eq;
- Human toxicity g.

Exercises (Impact assessment)

Mid point assessment table

Global Warming	943.89826	g CO2 eq
Ozone depletion	0.00064716	g CFC11 eq
Acidification	6.4787823	g SO2 eq
Carcinogenic	0.000362493	g PAH eq
Eutrophication	0.6554237	g PO4 eq
Heavy metal	0.041195347	g Pb eq
Summer smog	5.5089685	g C2H4 eq
Winter smog	4.14	g dust eq
Human toxicity	14.30546657	g



Bertoluci, G., & Millet, D. (2008). Functional product enrichment and supply chain disorganisation: two barriers for sustainable design [Figure 5]. International Journal of Product Development, 7, 149-169. Publisher: Inderscience Publishers Ltd.

End point Damage,
Valuation
Eco-Indicator?

normalization

distance to target

Exercises (Impact assessment)

Ecoindicator95

			Mid point	End point
Global Warming	943.89826	g CO2 eq	**1.45215E-13**	**1.21211E-11**
Ozone depletion	0.00064716	g CFC11 eq	**1.40687E-15**	
Acidification	6.4787823	g SO2 eq	**1.15693E-13**	
Carcinogenic	0.000362493	g PAH eq	**6.71284E-14**	
Eutrophication	0.6554237	g PO4 eq	**3.4496E-14**	
Heavy metal	0.041195347	g Pb eq	**1.52575E-12**	
Summer smog	5.5089685	g C2H4 eq	**6.18985E-13**	
Winter smog	4.14	g dust eq	**8.80851E-14**	
Human toxicity	14.30546657	g		

ISO: “weighting shall not be used for comparative assertions disclosed to the public”

Industrial Ecology

Compare the environmental impact of 3 products to provide mineral water:

1 glass bottle not reusable;
1 glass bottle reusable;
1 plastic bottle PET (poly(ethylene terephthalate))

+

+

Exercises (Simapro)

Product	Bottle	Cap	Label	Package
1 glass bottle reusable	Glass 599 g	Steel 2.2 g	Paper 1 g	PEHD 1818 g (12 bottle)
1 glass bottle not "	Glass 599 g	Steel 2.2 g	Paper 1 g	Paperboard 519 g (12 bottle)
1 plastic bottle PET	PET 18 g	PEHD 2.5 g	Paper 1 g	PELD 38 g

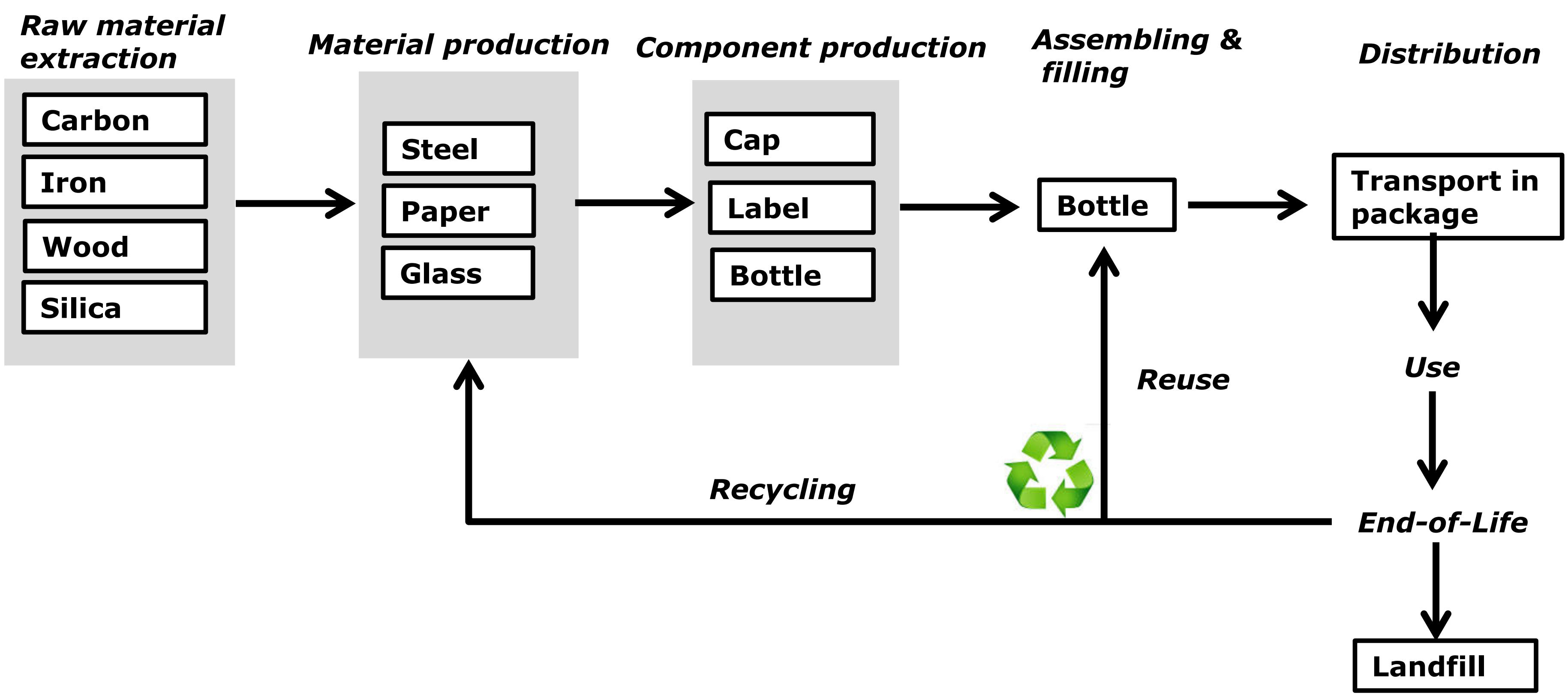
HD-High Density; LD-Low Density; PE- PolyEthylen; * Relatively to the market available

Product E-of-L	Reuse (%*)	Recycling (%*)	Landfill (%*)	Incineration (%*)
1 glass bottle reusable	70	10	20	-
1 glass bottle not "	-	40	60	-
1 plastic bottle PET	-	10	30	60

 E-mail: carla.silva@ist.utl.pt

Exercises (Simapro)

Simplified life cycle for reusable glass bottle



 E-mail: carla.silva@ist.utl.pt

Industrial Ecology – LCA module

Carla Silva

E-mail: carla.silva@ist.utl.pt

Principal investigator @ IDMEC

Researcher ID : A-4724-2012