Life Cycle Assessment

"LCA is a technique to assess environmental impacts associated with all the stages of a product's life from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling."

SETAC

(Society of Environmental Toxicology and Chemistry) 1993

LCA – Fields of Application

Application of LCA has become very widespread, ranging from production units to national systems. The LCA tool supports both direct users (producers of equipment), providers of services (electricity, water, energy, gas, waste disposal, mobility, communications, …) as well as final users and policy-makers…

Policies for sustainable development

- Communities
- Public companies

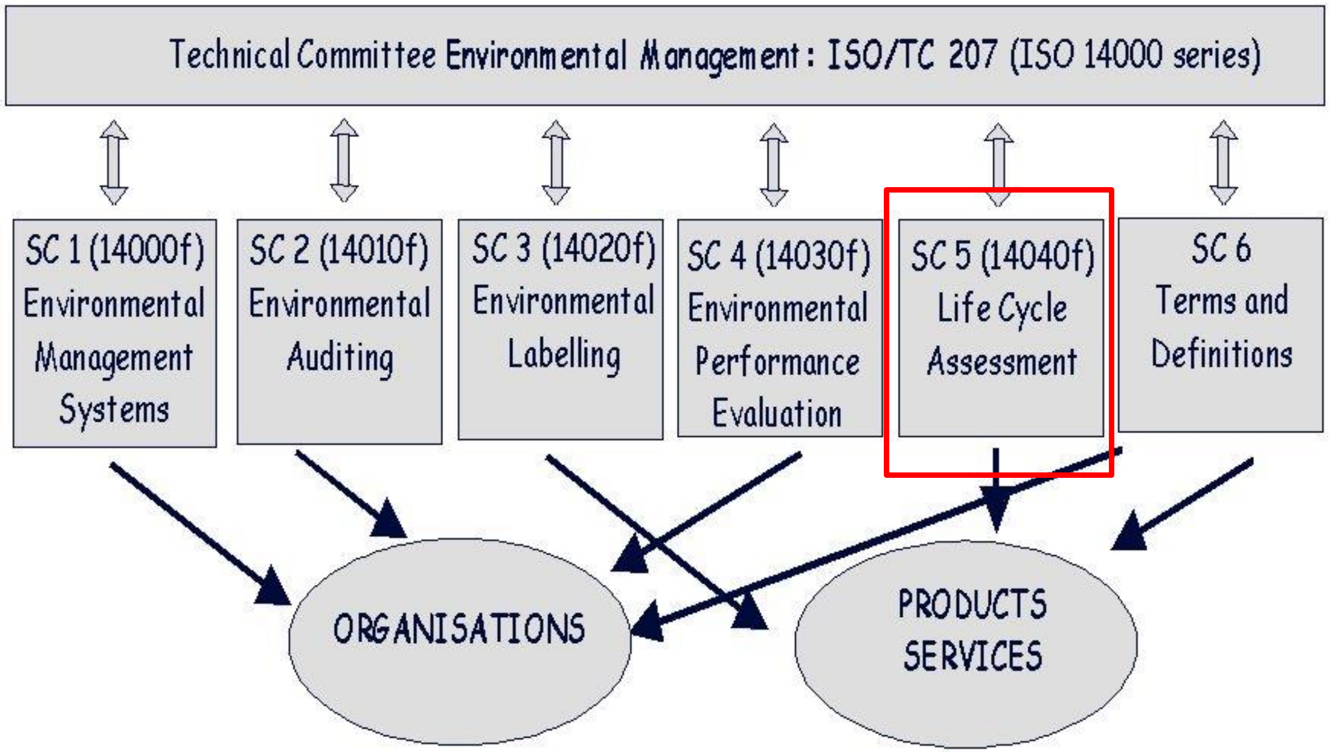
Private sector

- analysis of production (consumption, waste,…)
- compliance to laws and standards
- environmental certification of products and processes

LCA – European Approach

Europe has approved the EMAS environmental regulation which explicitly refers to application of LCA as a criterion for sustainability. The set of standars **ISO 14001** defines the application of LCA and confirm it as the appropriate tool for assessing environmental issues.

The European **Ecolabel** regulation, and the **ISO 14020** standards for ecologic labels prescribe the use of LCA as the only scientific instrument to assess truth of information about the environmental sustainability of products.



Voluntary

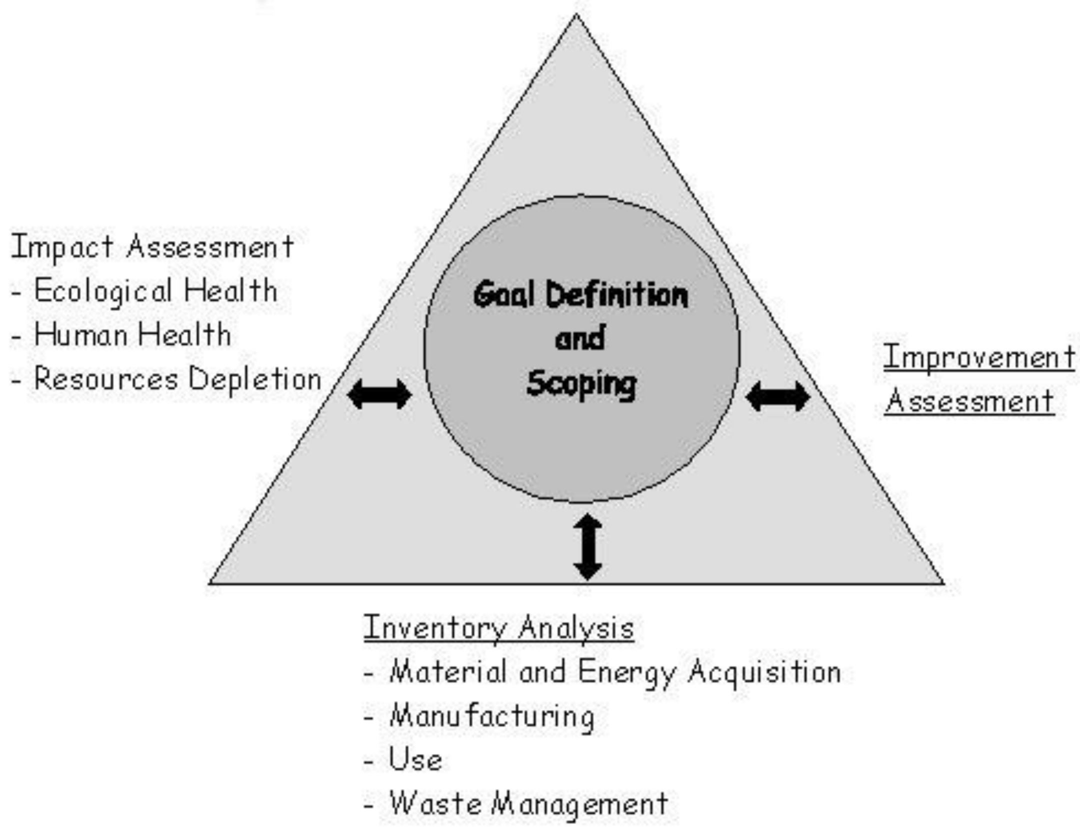
Instruments

But important for manufacturers (mass production goods, high quality,…)

LCA – ISO 14040

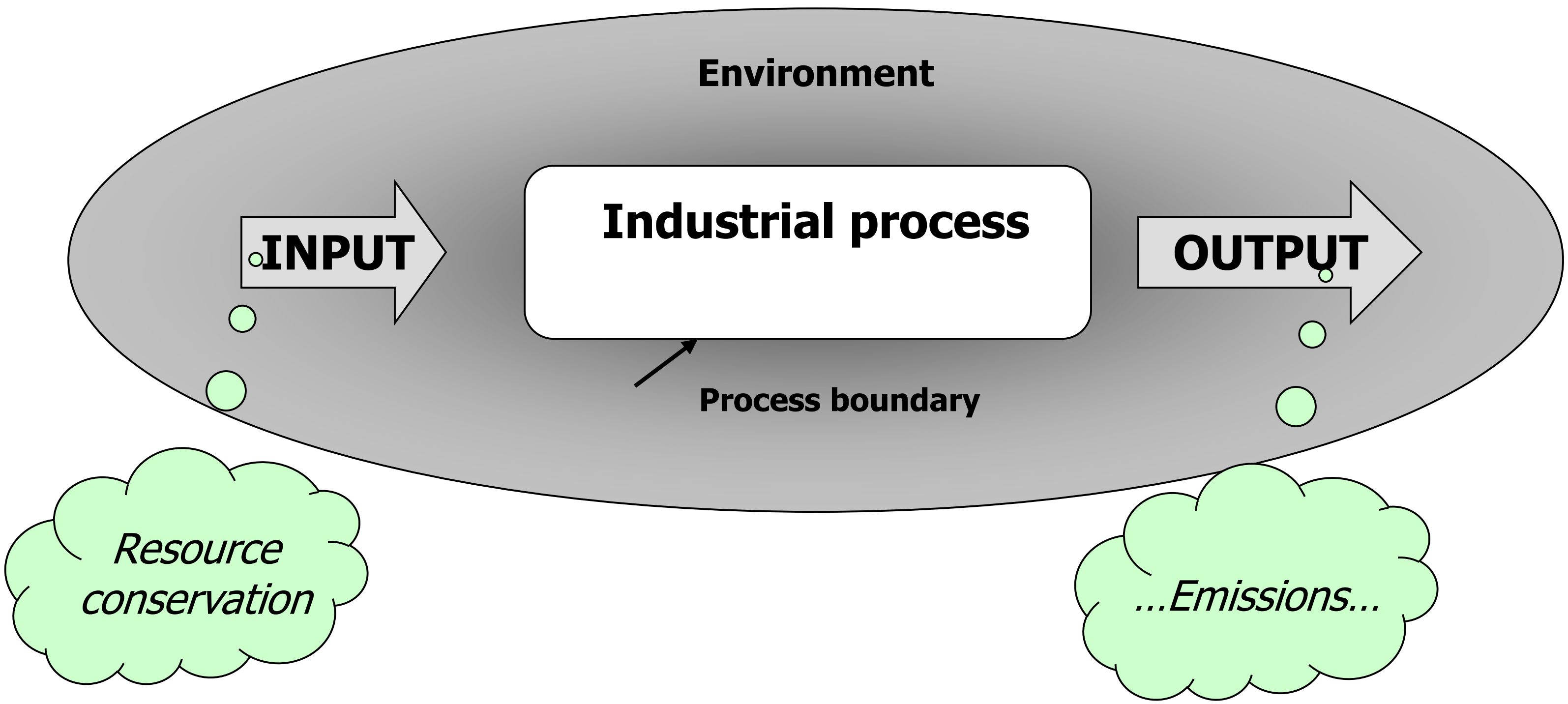
The ISO 14040 series represents an extension of the Guidelines proposed by SETAC.

- ISO 14040 (2006). Environmental management - Life cycle assessment - Principles and framework.
- ISO 14044 (2006). Environmental Management. Life Cycle Assessment. Requirements and Guidelines.



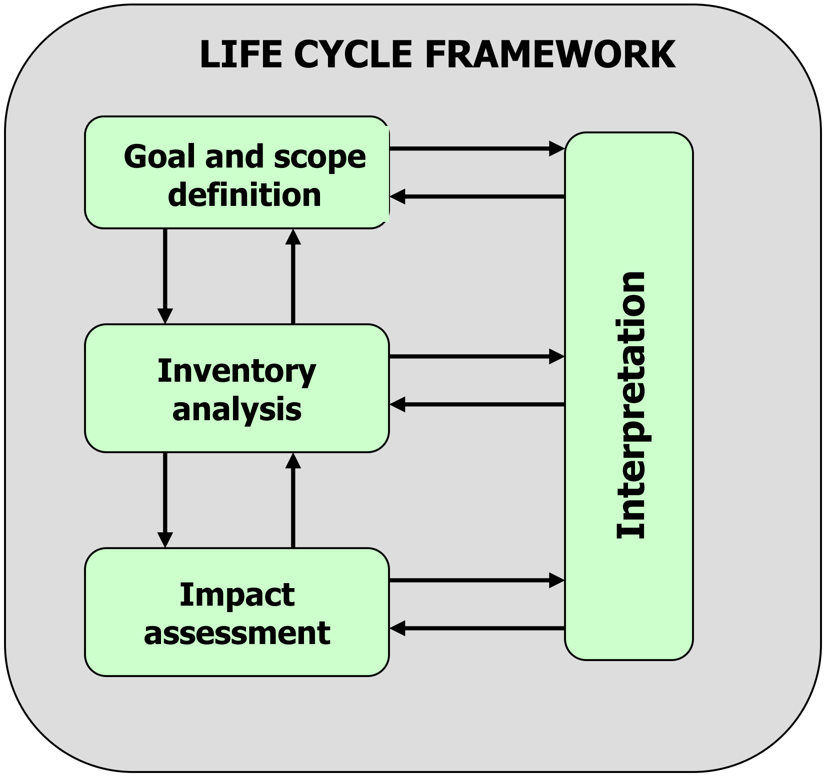
LCA - Definition

UNI EN ISO 14040 defines LCA as "… compilation and evaluation across the whole Life Cycle of input and output flows, and of potential environmental issues, connected to a productive system….".



LCA - Structure

The ISO 14040 standard identifies 4 steps for LCA:



- Goal and Scope Definition
- Inventory Analysis
- Impact Assessment
- Interpretation

The 4 steps interact among them as is common in Quality Systems.

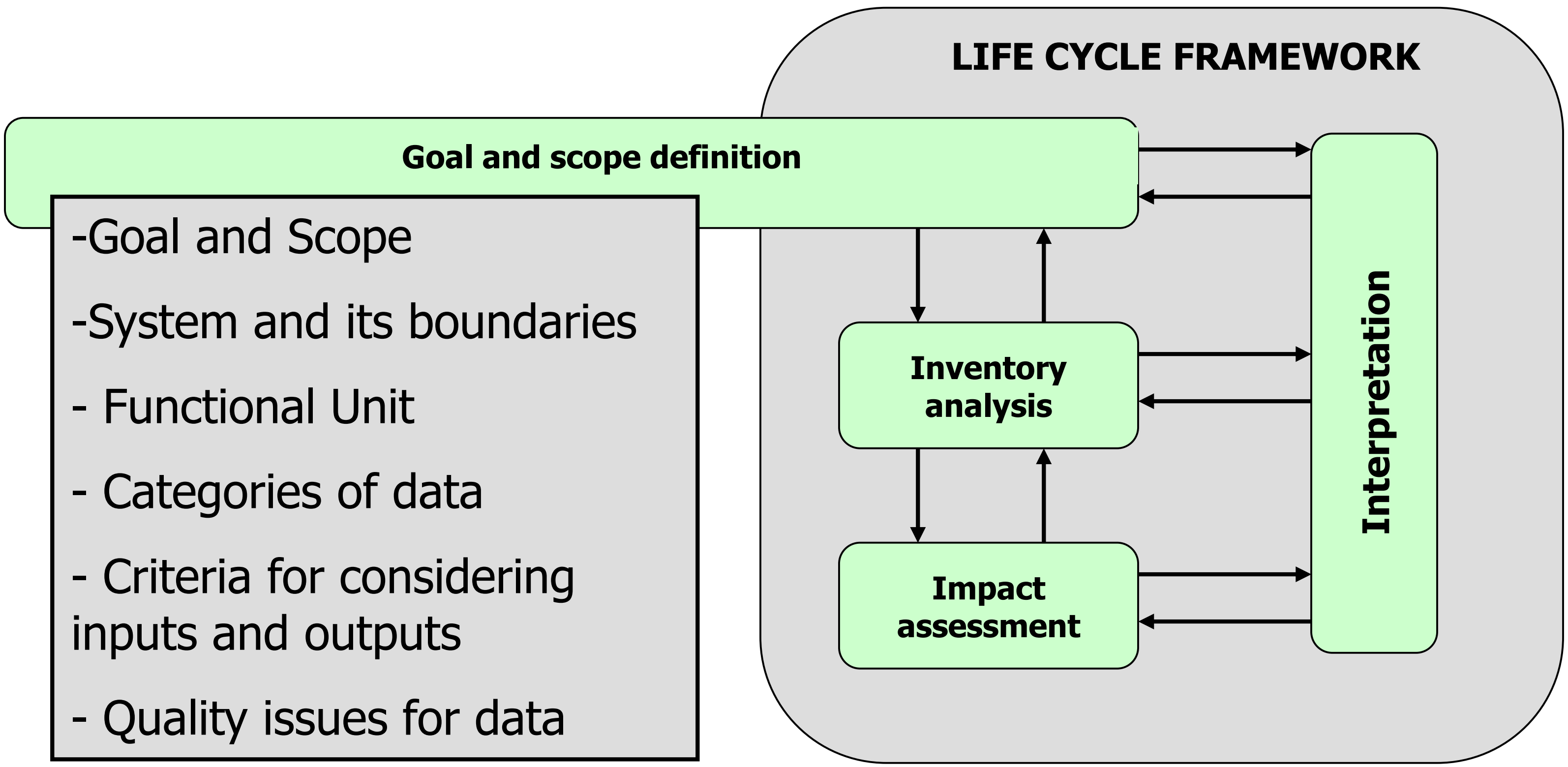
Iteration and revision of data, assumptions and boundaries are frequently necessary in LCA.

Goal and Scope - Purpose

The **purpose of the study** and its aim must be clearly defined. Examples:

- Industrial decision-making (multiple choices)
- Product assessment and certification
- Policies for taxation and price
- Presentation of sustainability options to communities

Different contents of reports



-Goal and Scope

-System and its boundaries

- Functional Unit

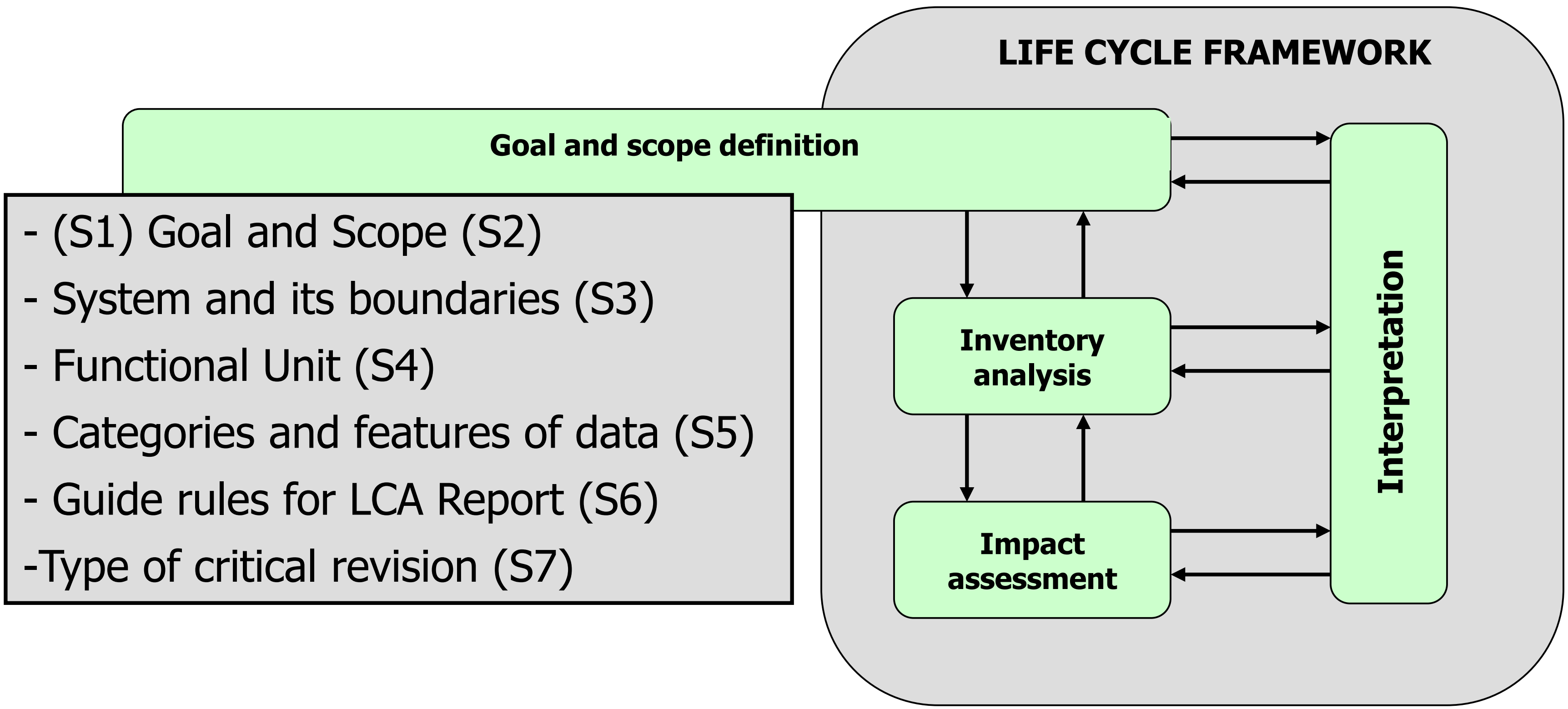
- Categories of data

- Criteria for considering inputs and outputs

- Quality issues for data

Goal and scope (S)

Goal (S.1) means definition of the case study and of the reasons behind it; its definition includes that of the audience, that is, to whom the issues of the study will be directed (technical/political/social). Scoping means defining in detail what are the (S.2) functions of the product or of the process which is under evaluation;

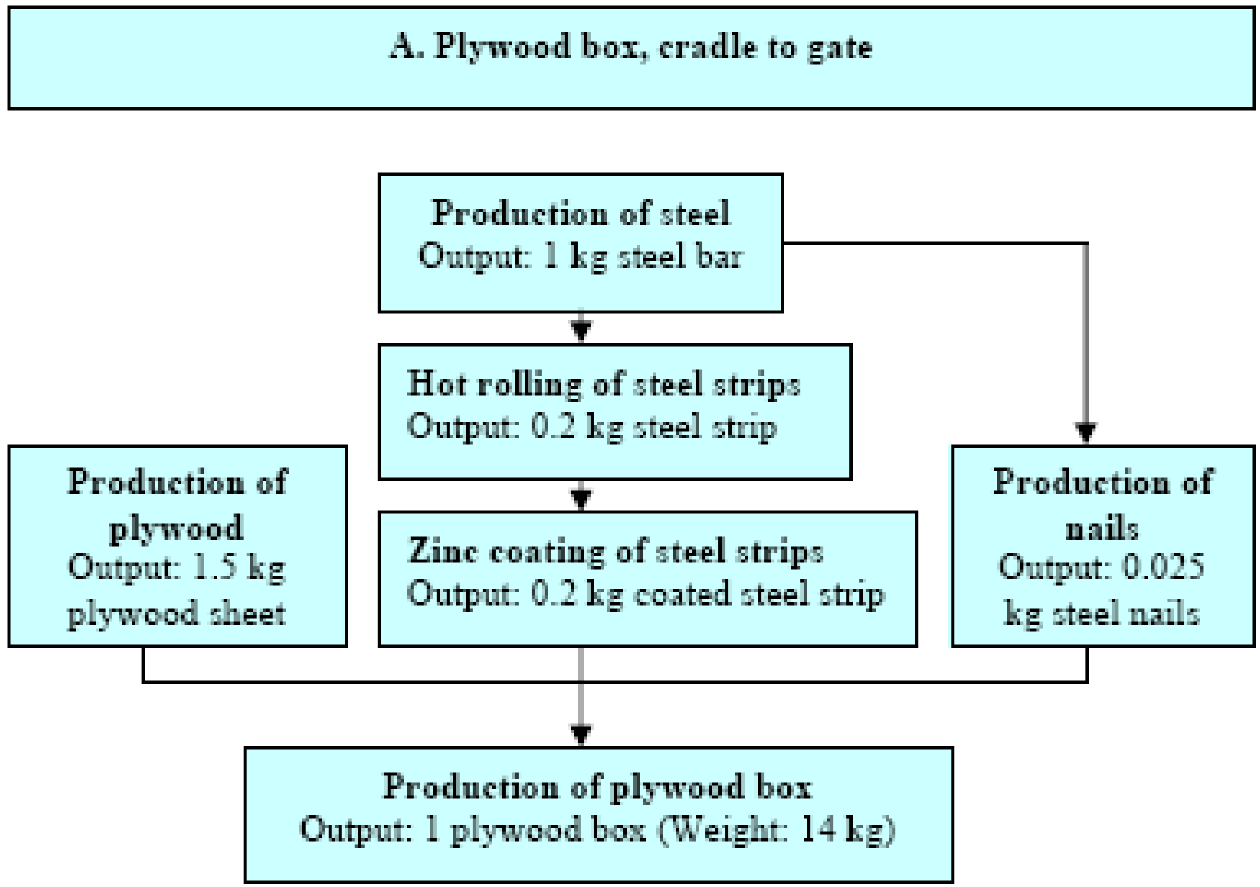


Example of Goal and Scope Definition:

Goal: Production of a plywood box *Function: Packaging of a product*
Possible Functional Units depending on the Goal and Scope definition
(see process schematic; list is not exhaustive):

- *g_{CO2} or kg_{CO2} to the environment per plywood box*
- *kg_{CO2} or tons of CO2 to the environment per year*
- *g_{CO2} to the environment per kg (unit mass) of plywood box*
- *g_{CO2} to the environment per kg of wood used in the process*
- *g_{CO2} to the environment per plywood sheet*
- *g_{CO2} to the environment per kg of steel*

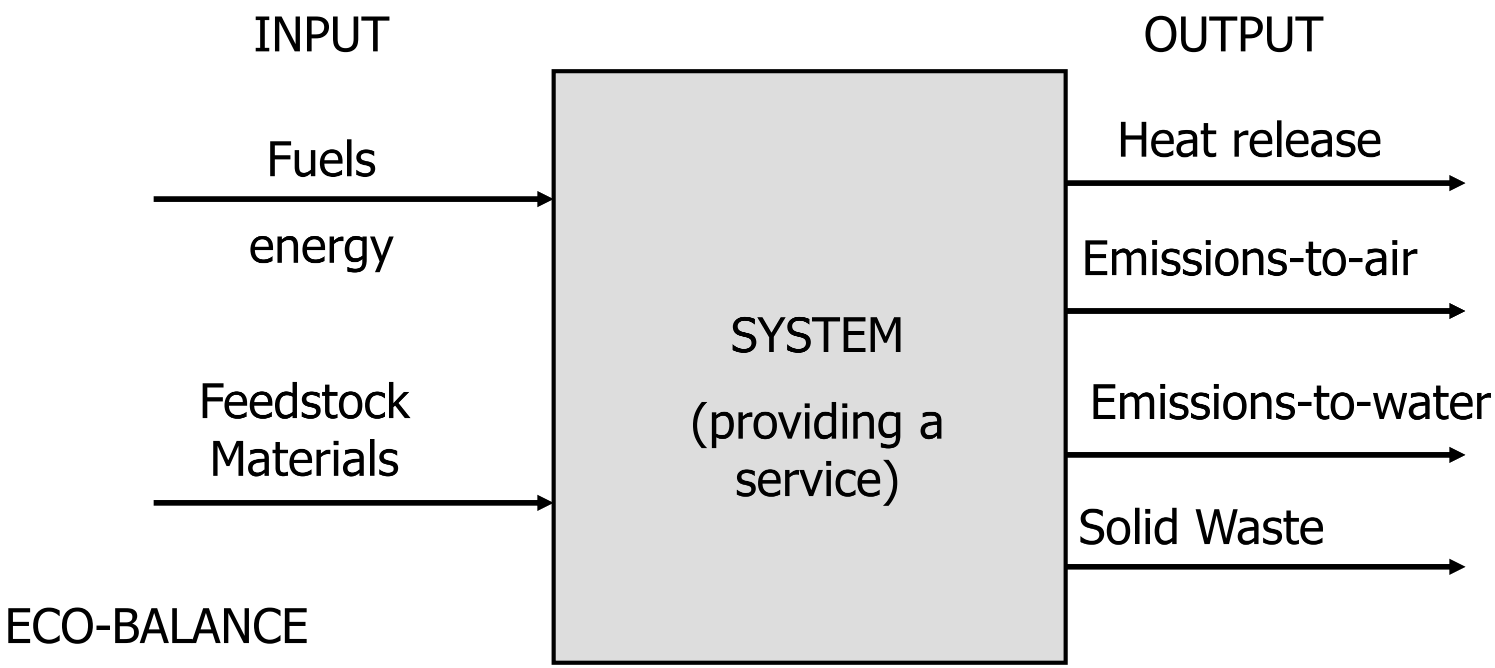
……….. From "Cascade – LCA training Package", Chalmers University, 2003



LCA – Definition of the system

The current trend is to try to aim at global systems: inputs are all resource matter or energy streams and outputs are only emissions to the environment ⇒

⇒ this is the true final Life Cycle - no useful product is left among the outputs.



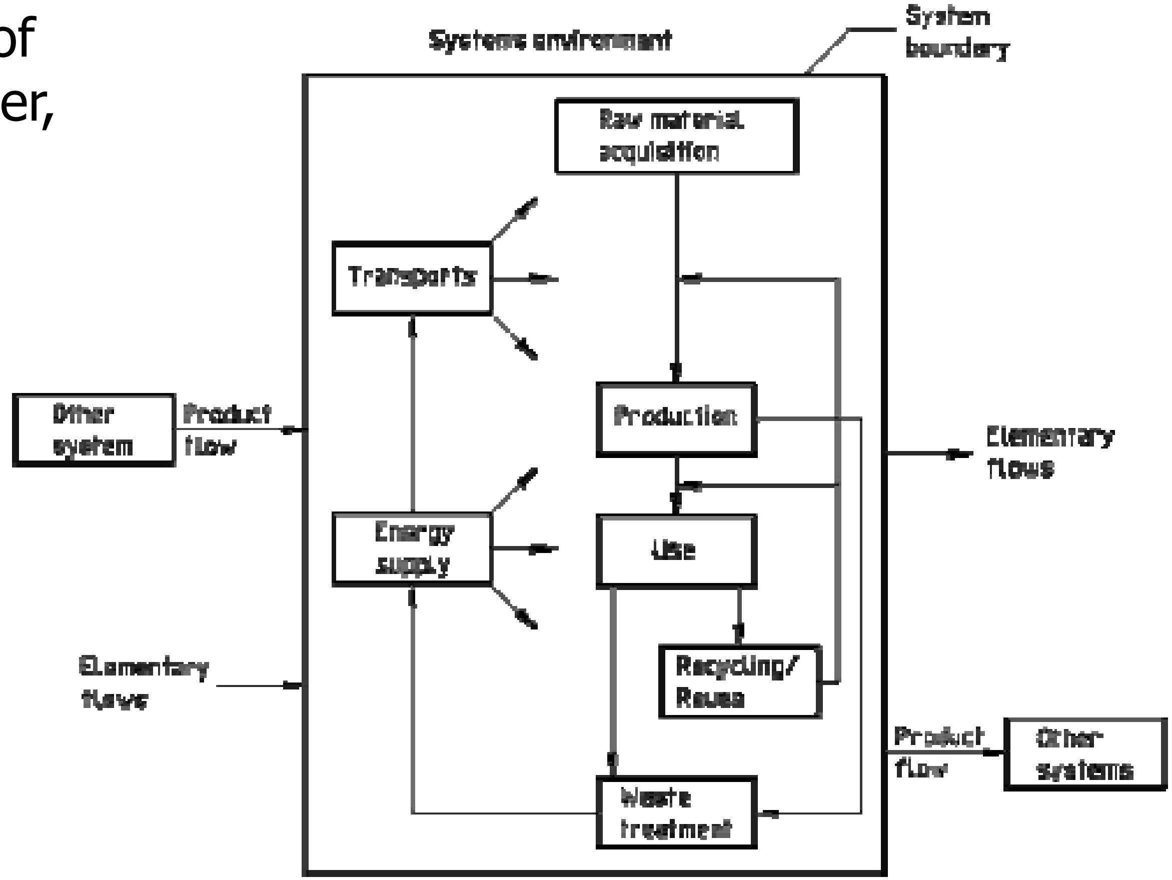
Example: a car, bus, train, ship or airplane is part of a larger process, providing mobility (a service, not a product).

LCA – System Boundaries (S.3)

Scoping includes the first definition of the system boundaries (S.3): however, these are often subject to changes during the Life Cycle Analysis, as a result of interaction among the different phases.

At the beginning, the system boundaries are often defined at the inlet of different raw material or intermediate products flows.

Proceeding with the LCA, one may realize that the boundaries of the system were not large enough, because a major environmental issue was not considered.



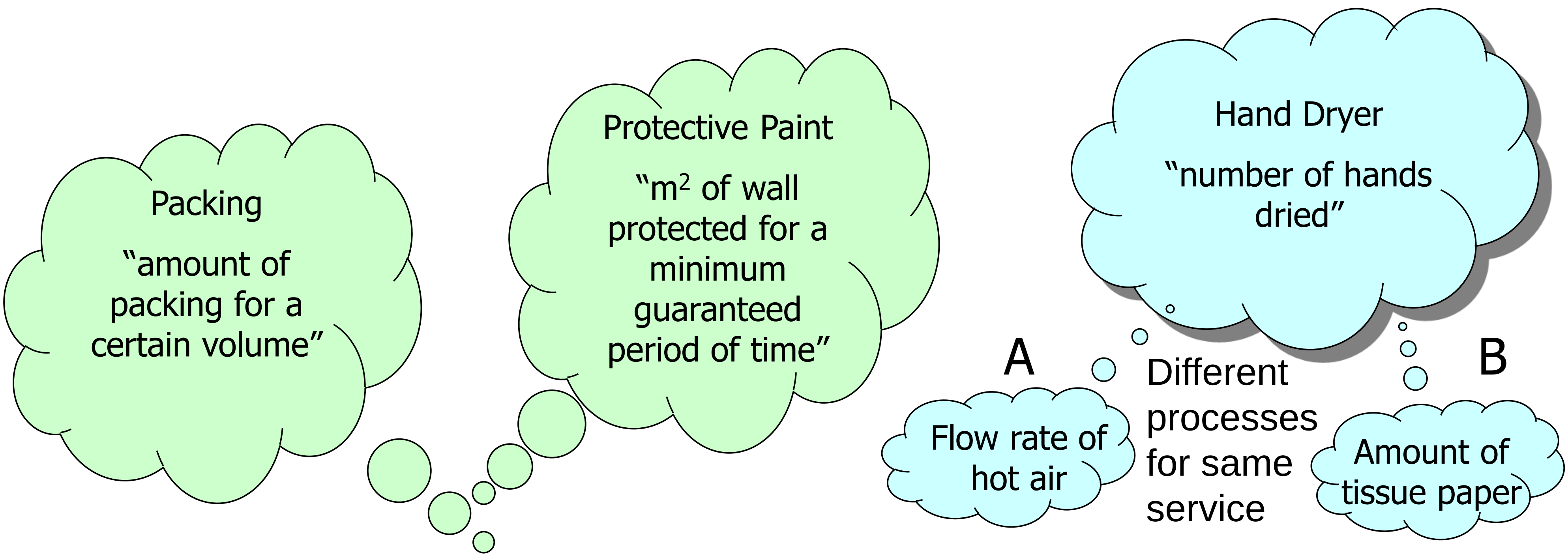
Example of definition of system boundaries

On the other side, improvement may suggest the introduction of internal recycling in the process, so that the system boundary needs to be adjusted (one or more waste streams can disappear).

LCA – Functional Unit (S.4)

All data and information of an LCA should be referred to a well-defined **Functional Unit** (S.4).

"A Functional Unit is a measure of the performance of the output flow of a process. The main purpose of the Functional Unit is to provide a reference to which all flows (input and output) are referred. The definition of a Functional Unit is necessary to allow comparison between LCA results. (ISO 14040)



LCA – Data, Reporting and Critical Revision

(S.5) Definition of data to be collected includes their accuracy, reliability and completeness.

Accuracy means an estimate of the average error (for example through the use of Uncertainty Analysis) ⇒ has to do with level of significance (later)

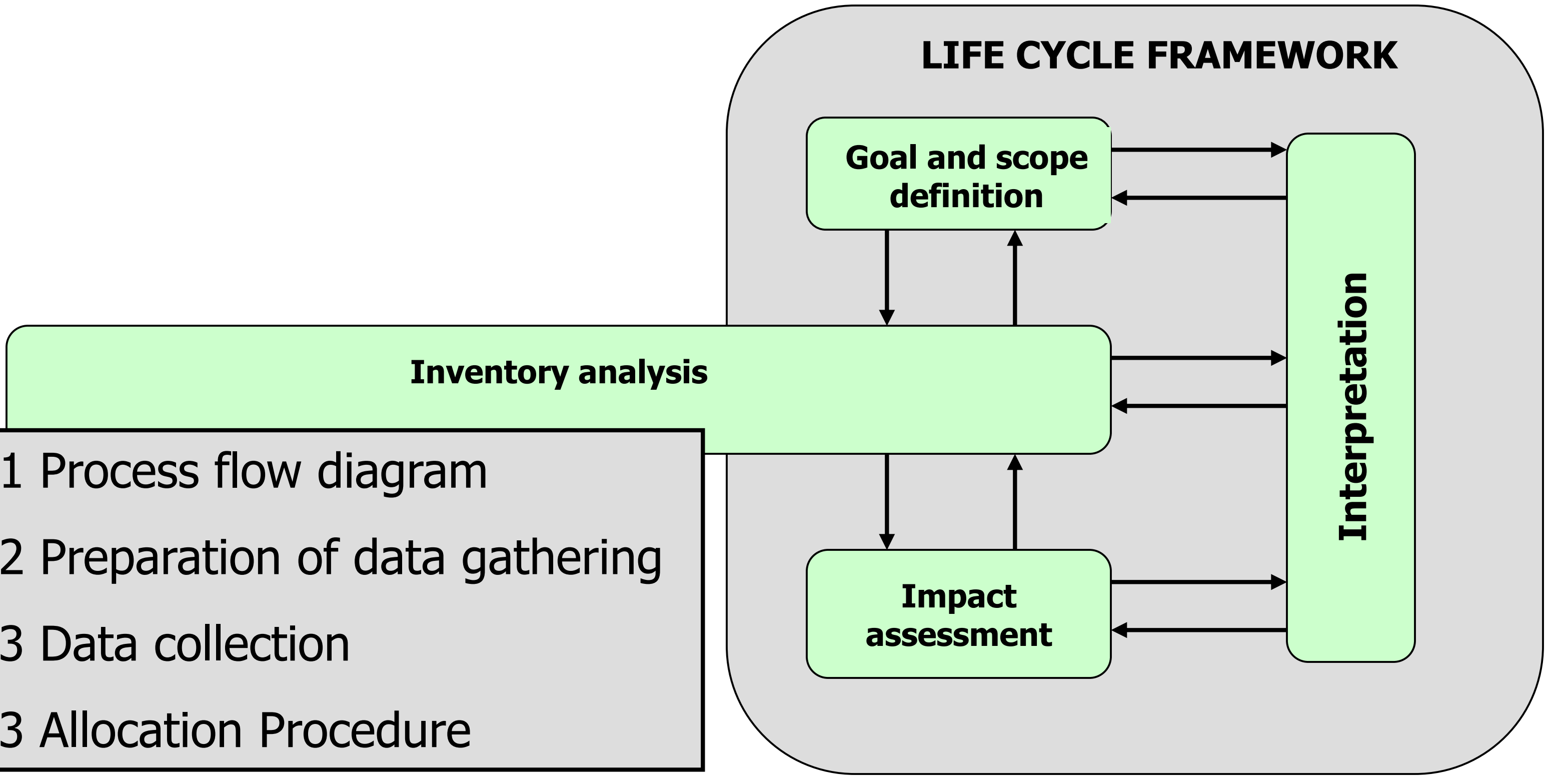
Reliability means for example that different sources for literature data should be considered, and their mutual agreement established ⇒ contradictions ?

Completeness means that quite often data series in time show "holes", that is, periods when historical data are not available. In this case one should consider techniques for substitution of missing data, and evaluate well if the boundary conditions were similar to those characterizing operation in periods of existing data ⇒ seasonal operation?

The final steps of the Goal and Scope Definition are providing (S.6) guide rules for preparation of the LCA Report, with the purpose of producing a document which is consistent with the objective of the study; and, finally, establishing which (S.7) type of critical revision should be applied to the LCA study (example: internal review; external review by experts/peer review; external by a certified third party;…).

LCA – Inventory Analysis (IA)

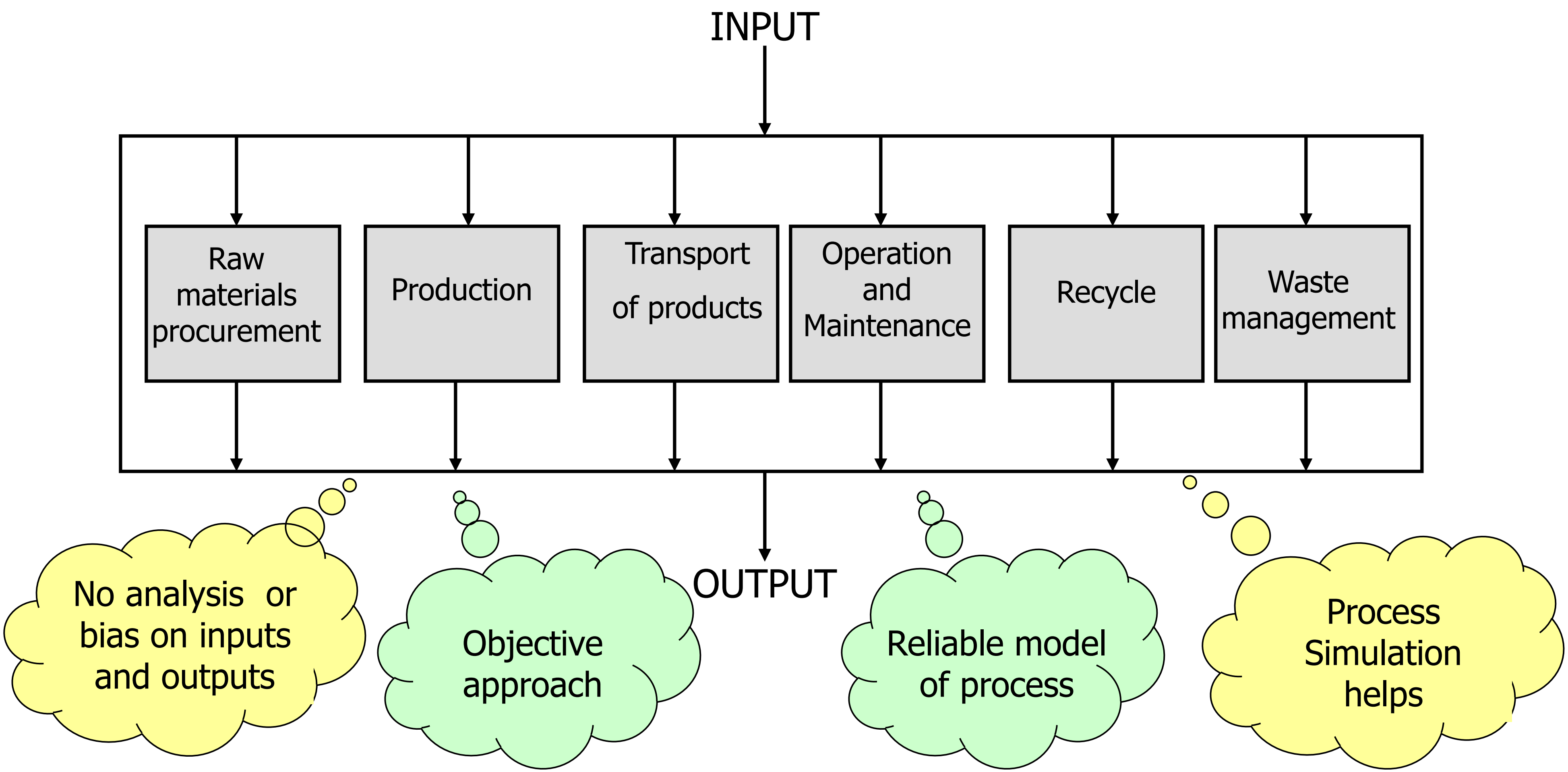
During this phase the flows of energy and materials throughout the production process are assessed, reconstructing thus the transformation from raw materials to final product; the issue is an ordered list of all inputs and outputs, which represents actually a model of the real system.



- IA1 Process flow diagram
- IA2 Preparation of data gathering
- IA3 Data collection
- IA3 Allocation Procedure

LCA - IA

A good **Inventory Analysis** is a key step in LCA: it allows to build a model representing closely the productive chain and its internal and external interactions. The IA includes many phases related to the complete Life Cycle.



LCA – IA.1 – Preparation for Gathering of Data

The first step is (IA.1) Preparation for gathering of data. This step is crucial for both success and efficiency of the study.

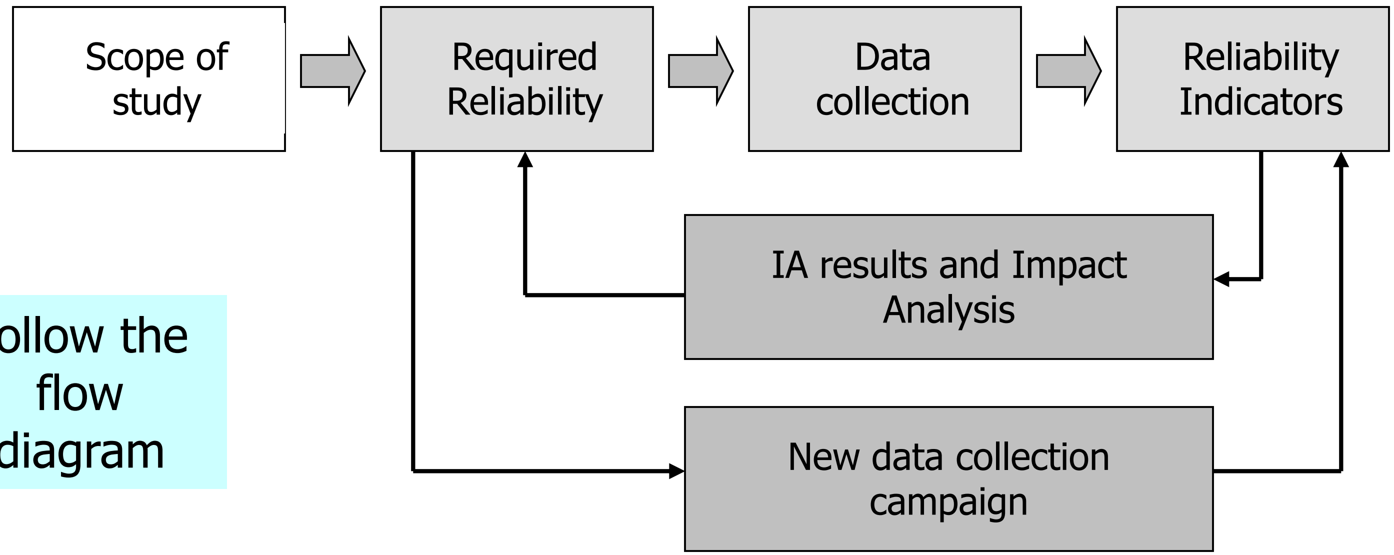
At first the process must be divided into sub-processes for which data must be collected; the type of data to be collected are defined, and what should be the format of data.

A detailed procedure for data collection is prepared, to be used by the operators.

Data collection includes defining the source of data: direct measurements, models or estimates; data bases or external reports; internal reports;…

LCA – IA.1 – IA.2

Specifications for Data collection include evaluation of the reliability of the data collected.



Assess the required degree of detail to be reached (e.g.: electrical consumption)

Follow the flow diagram

Use of direct data sheets

Primary data

Literature sources

Secondary data

Data Banks

LCA – IA.2 Data Collection

(IA.2) Data Collection is done by operators following the procedures defined in the previous step.
After collection, data must be validated; referred to the sub-process; scaled to the functional unit; Allocated and aggregated according to category (e.g. emissions of NOx in air) taking care not to duplicate immissions/emissions.

Validation means evaluating correctness of data, for example by a judgment of its trend in time or repetition of measurements

Referencing to the sub-process means scaling to the measurement unit of the exit of the sub-process.

Scaling to the Functional Unit means referring the mass flow at the exit of each sub-process to the flow of material required for production of one functional unit.

LCA – IA.2 Data Collection – Allocation and Category Selection

A critical point is often Allocation of data: usually different products are produced; it is thus necessary to allocate mass flows to each production line separating as far as possible inputs and outputs from common stock sources.

The matter is further complicated by recycling, which inside a factory is quite often done on a global scale, with interaction among different processes. This is a common reason for considering re-adjusting of the system boundaries.

Once the input/output flows have been assessed, it is possible to attribute them to relevant Categories (considering their environmental effects) following common LCA practice and/or a specific model. This is the link to the Impact Assessment step.

…Follows example…..

LCA_Eng.xls

Goal: Production of a plywood box *Function: Packaging of a product*

Functional Unit selected: g_{CO2} per plywood box produced.

With reference to Figure 2 scale all sub-processes to the functional unit; emissions of CO2 should also be allocated to wood, and – with reference to steel – to strips and nails separately.

The process does not include any recycling and transport is omitted.

One box is built out of 12 kg of plywood; 1,2 kg of steel strips and 0,6 kg of nails.

Process	CO2	Unit	Quantity per box	gCO2/box
Steel production	1210	g/kg of steel	1,8	2178
Roll sheeting of steel stripes	100	g/kg of stripe	1,2	120
Zinc coating of stripes	15	g/kg of stripe	1,2	18
Production of steel nails	120	g/kg of nails	0,6	72
Production of plywood sheet	128	g/kg of plywood sheet	12	1536
Production of box	178	g/box	1	178
			Total	**4102**
			2388	Steel

		Total steel	Total wood
1590	Stripes		
798	Nails	2388	1714

Production of one box implies emitting 4102 g of CO_2. Of these, 1536 are due to production of plywood sheet; for steel production, over a global emission of 2388 g of CO2 due to use of steel, the allocation can be traced to 1590 gCO2/box for steel stripes; and 798 gCO2/box for steel in nails.

LCA – IA – Data Banks

Data Banks are very useful but the reliability of the source must always be assessed and verified. It is quite common that data cannot be directly applied to the process under exam.

EcoInvent

CORINAIR

Boustead

I-LCA

I-LCD

Country energy mix

Transport emissions

Fonte dei dati	*NOx [mg/km]*	*CO [mg/km]*	*CO_2 [mg/km]*	*SO_2 [mg/km]*	*Consumo [g/km]*
BOUSTEAD MODEL V.4.2	1.800	1.500	149.000	38	40
CORINAIR 1997	2.560	10.000	140.000	34	45

Check:

- Literature source
- Age of data (< 10 yrs)
- Check for consistency with other sources

LCA – Inventory Analysis Results

Usually the results of an Inventory Analysis are represented in 6 groups:

- Raw materials
- Fuels
- Energy content of feedstock
- Solid Waste
- Emissions-to-Air
- Emissions-to-Water

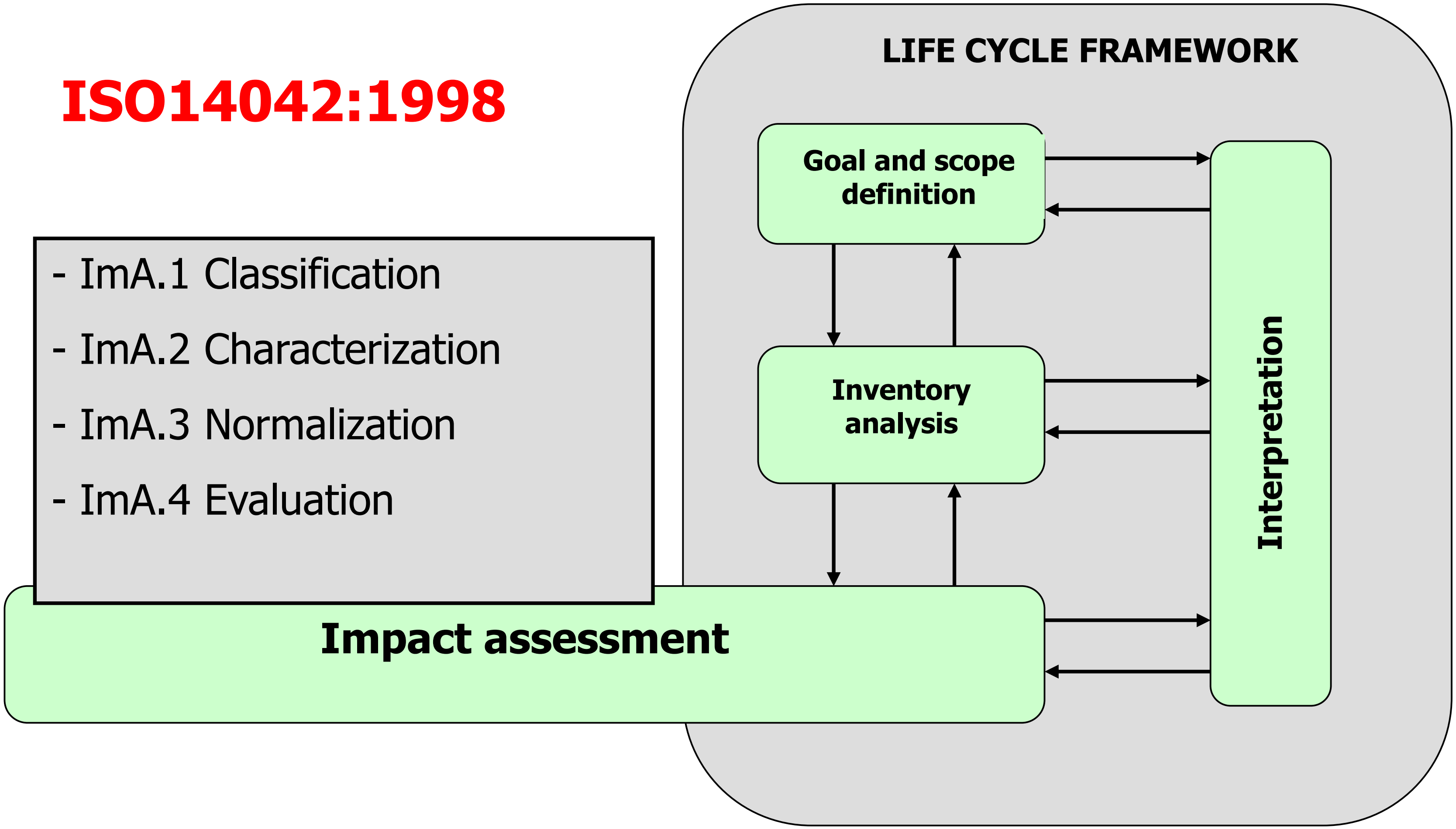
Energy content of feedstock: the energy content of the materials to be transformed in the process (not to be used as fuel)

LCA – Impact Analysis - ImA

Info gathered in the Inventory Analysis represents the starting point for the *Life Cycle Impact Assessment*.

ISO14042:1998

- ImA.1 Classification
- ImA.2 Characterization
- ImA.3 Normalization
- ImA.4 Evaluation



LCA – ImA – Generalities

Impact Assessment has the purpose to identify the size of environmental modifications produced by releases to the environment (emissions or waste) and by the consumption of natural resources connected with the productive process.

Impact: in LCA terminology, it represents the physical result of an operation within th process – specifically, the emission of substances

One impact can be due to one or more environmental effects

Environmental effects

Global

Regional

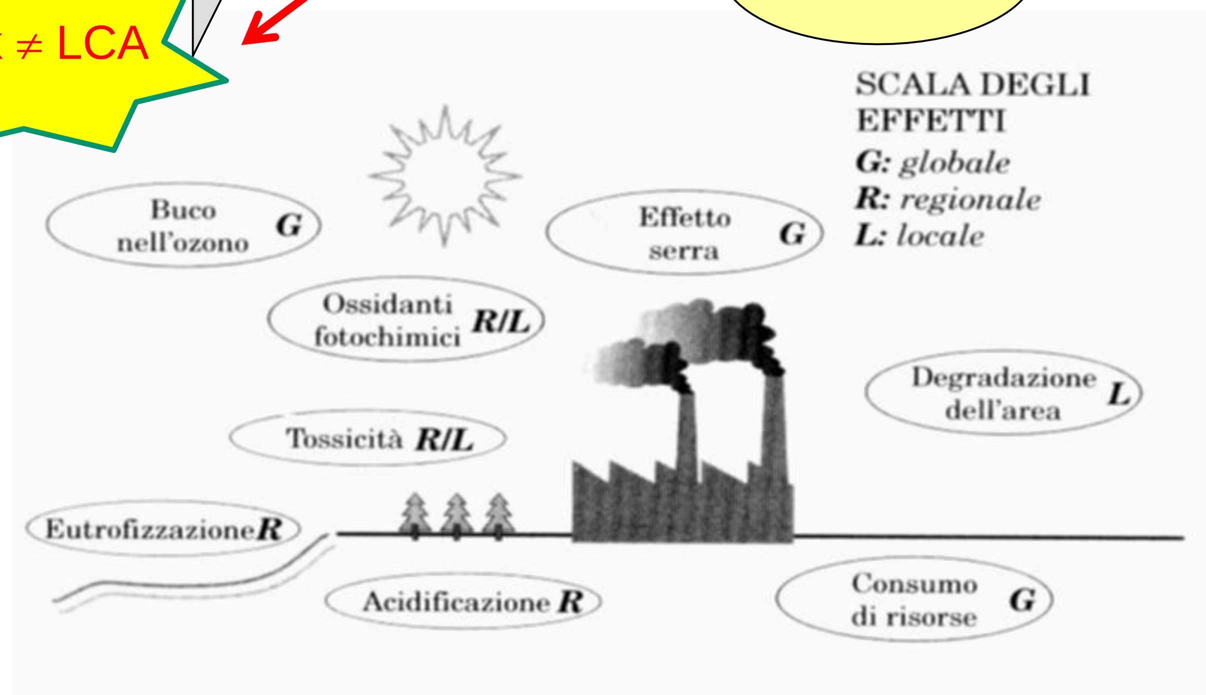
Local

Risk ≠ LCA

Expected Result of Impact Analysis:

Complete environmental profile allowing comparison among process alternatives

Minimization of impact of production process



LCA – ImA – Mandatory and Non-Mandatory

LCA Impact assessment has inevitable limits in its objectivity.

Different environmental issues can be of much different concern to the local audit, depending on traditions, climate conditions, etc. However, there are well-established rules and trends that have allowed the development of largely accepted assessment methods.

Impact Assessment is divided into a Mandatory Section and an Non-Mandatory Section.

The Mandatory Section starts from (ImA_mand.1) the Selection of impact categories; category indicators and characterization models. Already at this stage it is common practice to refer directly to an assessment method, e.g.: Eco-Indicator 95/99; Recipe Mid-Point or End-Point; EPS; EDIP; ILCD.
These methods feature user-ready impact categories.

LCA – Impact Categories - Grouping

LCA ImA started from detailed categories; the current trend is favouring Grouping of Categories in order to promote comparability among methods. Main Groups (EndPoint):

- *Ecology:* effects on biodiversity of the ecosystem (*ecological effects*)
- *Health* : effects on health and safety of mankind (*human health and safety effects)*
- *Resources*: exhaustion of energy and raw material resources *(resource depletion)*
- *Social effects*: impact on human activities connected to the system and the induced *(habitat degradation)* → ***S-LCA (Social LCA)***

ENDPOINT

Ecological Effects	Greenhouse Effect	kg CO_2
	Ozone Layer Depletion	kg CFC11
	Acidification	kg SO_2
	Eutrophication	kg PO_2
Human Health	Summer Smog	kg C_2H_4
	Winter Smog	kg SPM
	Heavy Metals	kg Pb
	Carcinogenics	kg B (a) P
	Pesticides	kg act. s.
Resource Depletion	Solid Waste	kg
	Primary Fuel Consumption	MJ
	Water Consumption	kg

Eco-Indicator 95 (or MidPoint)

EI95 MP = 11 Categories

LCA - ImA - Classification

The second step is (IA_mand.2) Classification, that is, assignment of the results of the inventory analysis to the different impact categories identified.

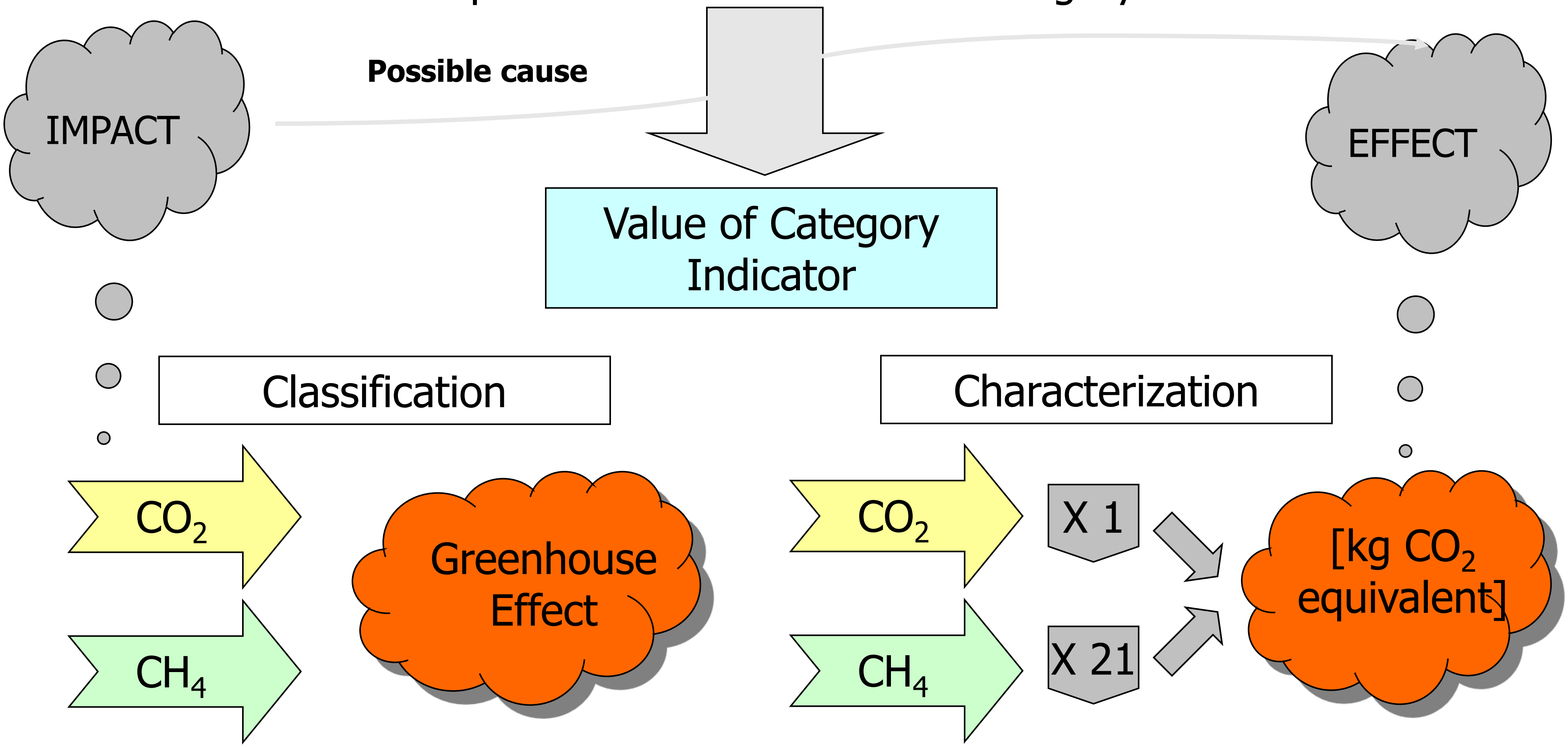
Some emissions may impact on different categories.

Classification is often automatically done following the rules defined in the selected method of assessment.

Impact	**HCFC22**	**CH4**	**TOLUENE**	**SO2**	**NOx**
Greenhouse Effect	**X**	**X**	**X**		
Ozone layer depletion	**X**	**X**			
Acidification				**X**	**X**
Summer Smog					**X**

LCA – ImA - Characterization

The third step is (IA_mand.3) Characterization; the result is the **category indicator**. This implies multiplying the result of the inventory analysis with appropriate characterization factors for different streams of matter – depending on the contribution of a specific substance for each category.



Up to Characterization: Mandatory part of LCA….

Eco-Indicator 99 (End Point) refers to three impact categories:

Eco-Indicator 99		
Impact category	Category Indicator	Measurement Unit
Ecosystem Quality	Potentially Disappeared Fraction (PDF)	PDF*m2*yr
Human Health	DALY (Disability Adjusted Life Years) Average Life Expectancy	Yr*person
Resource	Direct damage to resource	MJ/kg

ImA - Human Health – DALY

Damage to Human Health is expressed in DALY (Disability Adjusted Life Years).

1 DALY : loss of 1 year of life by one individual (or, for example, 25% invalidity for 4 years).

Models for DHH have been assessed for respiratory health damage, carcinogenics, greenhouse effect, ozone layer depletion and ionized radiations. WHO data are often used as reference.

The evaluation of damage needs 4 steps:

- Fate analysis: emission of a given substance (in mass, g/s) is linked to a temporary variation of its concentration in the environment.
- Exposure analysis: the concentration level is trandlated into the dose per local exposed population.
- Effect analysis: statistical data correlating exposure and health effects are processed
- Damage analysis: the health effects over the population are expressed in terms of DALY, applying models for Years Lived Disabled (YLD) and Years of Life Lost (YLL).

ImA - Ecosystem Damage

Ecosystem Damage is expressed in terms of species disappearing in a reference area because of damage to the environment (PDF = Potential Disappeared Fraction of Species).

-Ecotoxicity is in general evaluated considering the % of species present in the environment and affected by the emissions. Empirical methods are available to produce rough estimates of the ovreall toxicity stress and convert it into an observable damage (PDF).
-"Acidification and Eutrophication" are treated as one single damage category to the environment; for this category validated models for the evaluation of Ecosystem damage in PDF are available.
- Also for the environment the process applied for health damage is replicated (Fate analysis - Effect analysis - Damage analysis)
-"Land-use and land transformation" is a specific category for Ecosystem Damage; damage is evaluated considering empirical data about survival potential of vegetable species depending on the use and extension of land.

PDF·m^2·yr (Potential Disappeared Fraction of Species): a damage of 1 unit means that all vegetable species disappear from the unit area (1 m^2) after 1 year; alternatively, that 1% of vegetable species disappear in 10 m^2 after 10 years.

ImA – Resource Depletion

In LCA, **Resource Depletion** is measured as the additional energy needed to extract the resource from the environment, which is increasing as a consequence of progressive depletion.

ImA Resource Depletion is composed of two sub-phases:

Resource analysis, (similar to fate analysis) links the extraction of resources with the decrease of available resources.

Damage analysis, links the lower availiability of resources with additional energy required to extract them.

The measurement unit is the MJ Surplus Energy , which can be referred either to unit mass (kg, ton) or (as is common for fuels) to the calorific value, MJ_{res}/MJ_{PCI}: this last formulation expresses the energy needed to extract 1 MJ to be used as fuel.

Example: A company wishes to evaluate two products performing the same function.

	Name	Quantity A	Quantity B	Unit	Human Health Charact. Factor DALY/kg	Potentially Disappeared Fraction Charact. Factor PDF m2 yr/kg	Potential Resource Depletion Charact. Factor MJ/kg or MJ/MJ	A-Cumulative	B-Cumulative
Resources									
	Natural Gas		1,85	MJ			1,78E-05	0,00E+00	3,29E-05
	Oil	5,655		kg			7,02E-04	3,97E-03	0,00E+00
	Hard Coal	0,5348	0,5348	MJ			1,02E-06	5,45E-07	5,45E-07
	Lead Mineral Ore	0,0586		kg			4,38E-05	2,57E-06	0,00E+00
	Nickel Mineral Ore	0,896	0,786	kg			2,91E-05	2,61E-05	2,29E-05
	Zinc Mineral Ore	0,262	0,282	kg			2,24E-04	5,87E-05	6,32E-05
						Overall	**MJ**	**4,06E-03**	**1,20E-04**
Human Health									
	Methylene Chloride	0,67	0,348	kg	1,23E-04			8,24E-05	4,28E-05
	Methane	0,007862	0,00572	kg	2,86E-04			2,25E-06	1,64E-06
	Cadmium	9,82E-05		kg	8,77			4,31E-04	0,00E+00
	Exachlorobenzene	0,009717	0,006124	kg	5,36			5,21E-02	3,28E-02
	Nickel	0,000197	0,000128	kg	1,53			3,01E-04	1,96E-04
	Formaldehyde	0,001937	0,000837	kg	6,44E-05			1,25E-07	5,39E-08
	CO2	1,869	2,551	kg	1,36E-05			2,54E-05	3,47E-05
	Chloroformium	7,27E-05		kg	5,39E-05			3,92E-09	0,00E+00
	NO		0,5698	kg	4,48E-03			0,00E+00	2,55E-03
						Overall	**DALY**	**5,29E-02**	**3,57E-02**
PDF	Copper	0,00186	0,00164	kg		2,85E-01		5,30E-04	4,67E-04
	Lead	0,000179		kg		4,95E-01		8,84E-05	0,00E+00
	Cadmium	9,82E-05		kg		1,88		9,23E-05	0,00E+00
	Benzene	0,0687		kg		5,36E-07		3,68E-08	0,00E+00
	Pentachlorophenol		0,00789	kg		2,59E-03		0,00E+00	2,04E-05
						Overall	**PDF m2 year**	**7,11E-04**	**4,88E-04**

Notice: Cadmium contributes to 2 categories, the flow rate is divided by two.

Results of the Life Cycle Inventory and of characterization according to the Eco-Indicator 99 methodology.

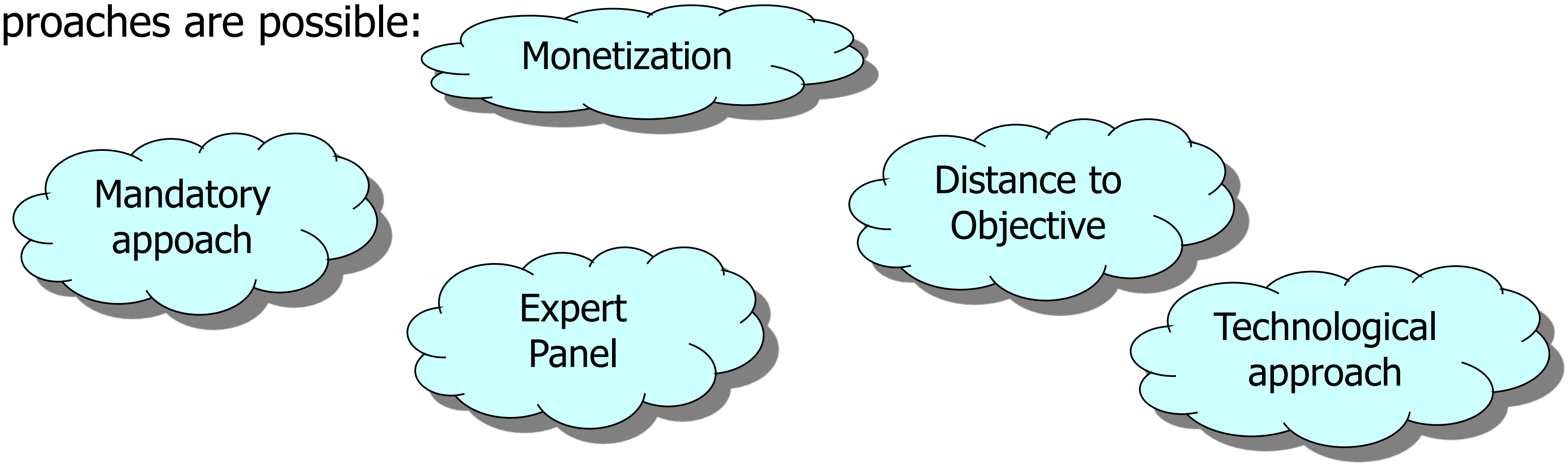
Product B provides lower category indicators in all three categories, and is thus preferable with respect to Product A.

LCA_Eng.xls

LCA – ImA – Non-Mandatory - Normalization

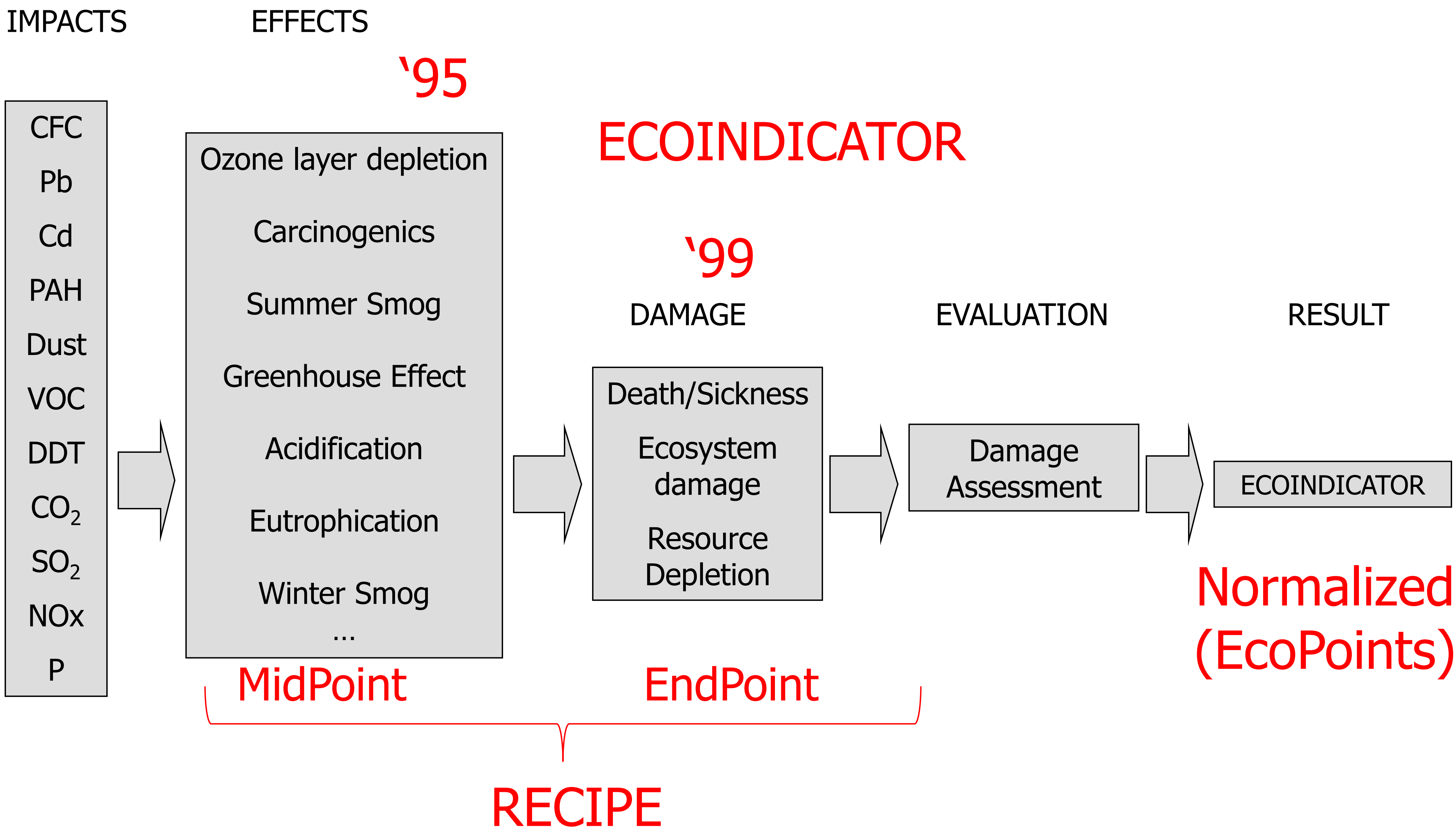
Normalization reduces the complete environmental performance profile to one single synthetic parameter. This is an Optional section of LCA, because it is difficult to reach a universal agreement about construction of the final parameter.

Normalization is however very useful for comparing options and final decision-making. Several approaches are possible:



EcoIndicator is a widely accepted normalization method in Europe. It assumes that emissions are located in Europe and restricts damage assessment to this region: however, damages to Resources are accounted as global effects, as well as: Climate Change (Greenhouse), Ozone layer depletion, long-range carcinogenics and inorganic and radioactive pollutants.

LCA – ImA – Normalization – Ecoindicator, Recipe



LCA – ImA- Normalization - Weighting

"Eco-Indicator 99" or Recipe consider three different time perspectives for environmental assessment.

-*Egalitarian*: Long-Term View; even a minimal scientific evidence justifies considering an effect.

	Normalisation	Weights
Human health	1.55E-02	300
Ecosystem Quality	5.13E+03	500
Resources	5.94E+03	200

-*Individualist*: Short-Term View;

Only proven effects are included.

	Normalisation	Weights
Human health	8.25E-03	550
Ecosystem Quality	4.51E+03	250
Resources	1.50E+02	200

-*Hierarchist*: Mid-Term View; inclusion of an effect is based on current scientific acceptance.

Hyerarchist is the most commonly applied weighting method.

Category	Normalization	Weight
Human Health	1,54 *10^-2	400
Ecosystem Quality	5,13 *10^3	400
Resource Depletion	8,41 *10^3	200

Note: for any perspective, the sum of weights is always 1000!
See triangular diagram in the following …

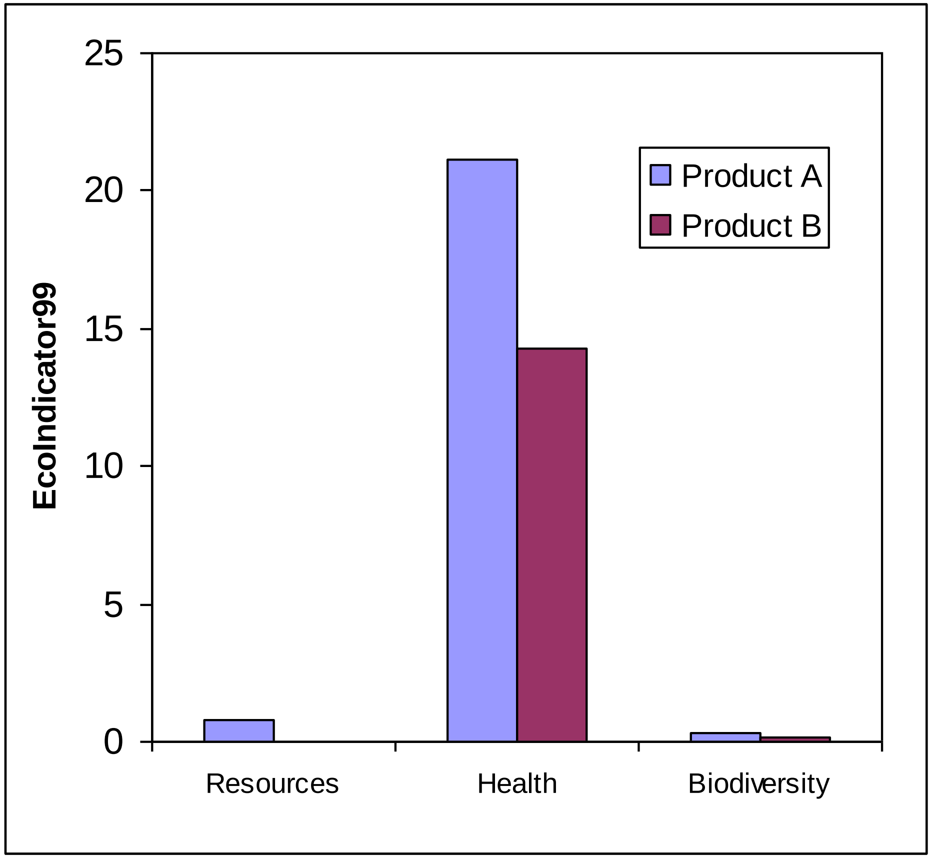
As prescribed in the ECOIndicator99 method, "Hierarchist" perspective, health and bio-diversity scores are multiplied by a weighting factor 400; resource damage is weighted by a factor 200.

(Interpretation...)

Ending the Interpretation LCA Phase, one should in this study stress that – even if Product B is superior to product A for all damage categories – the main impact is on human health.

Going to further detail, one could notice that the largest improvement passing from product A to product B is reduction of resource depletion.

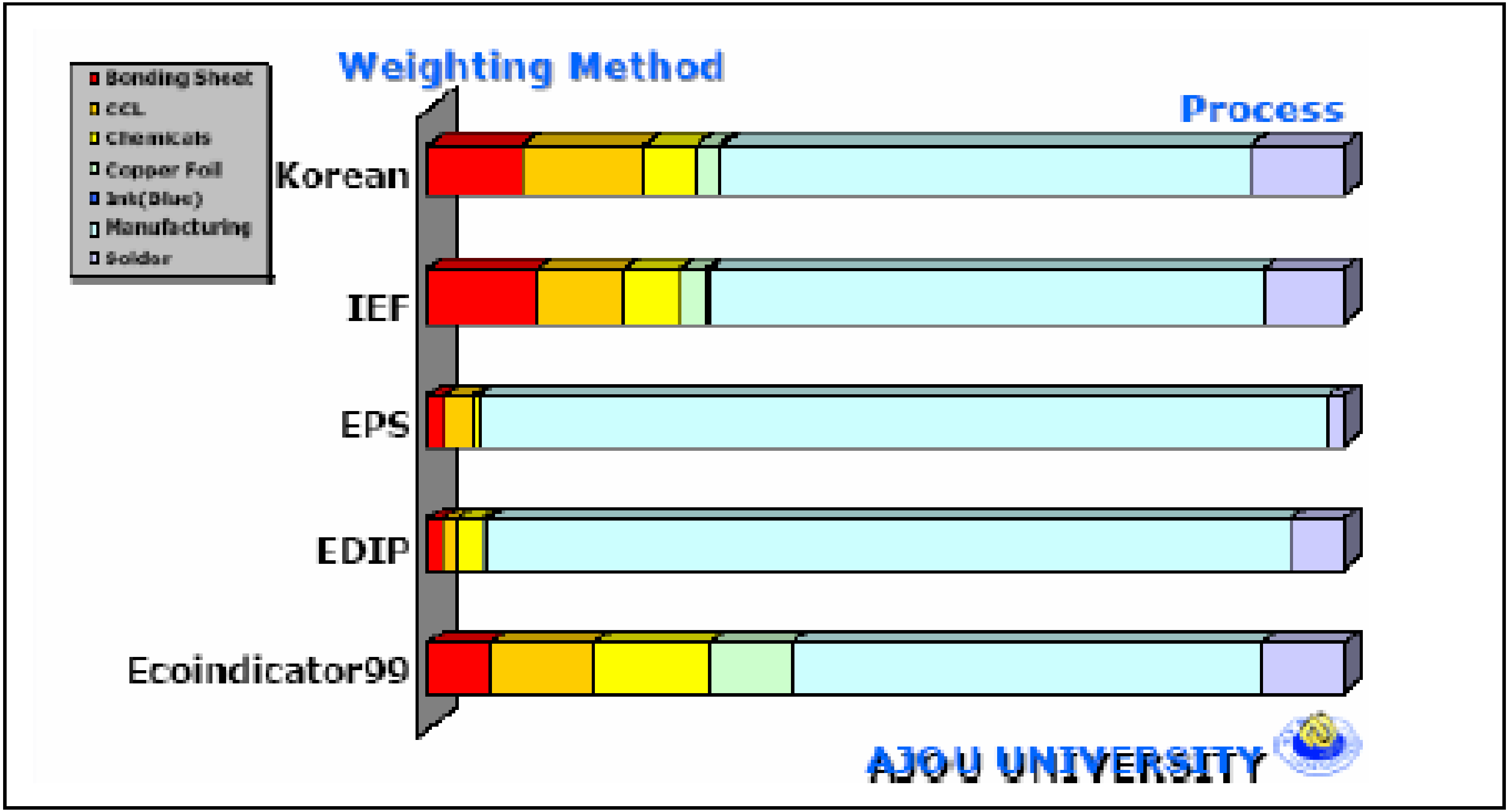
From this point of view, the new process (B) does not seem to be completely satisfactory, as it fails to address preferentially the main impact category, which is the effect on human health.



	A	B
Resources	0,812	0,024
Health	21,170	14,261
Biodiversity	0,284	0,195
EcoIndicator99	**22,266**	**14,480**

Normalization (Weighting)

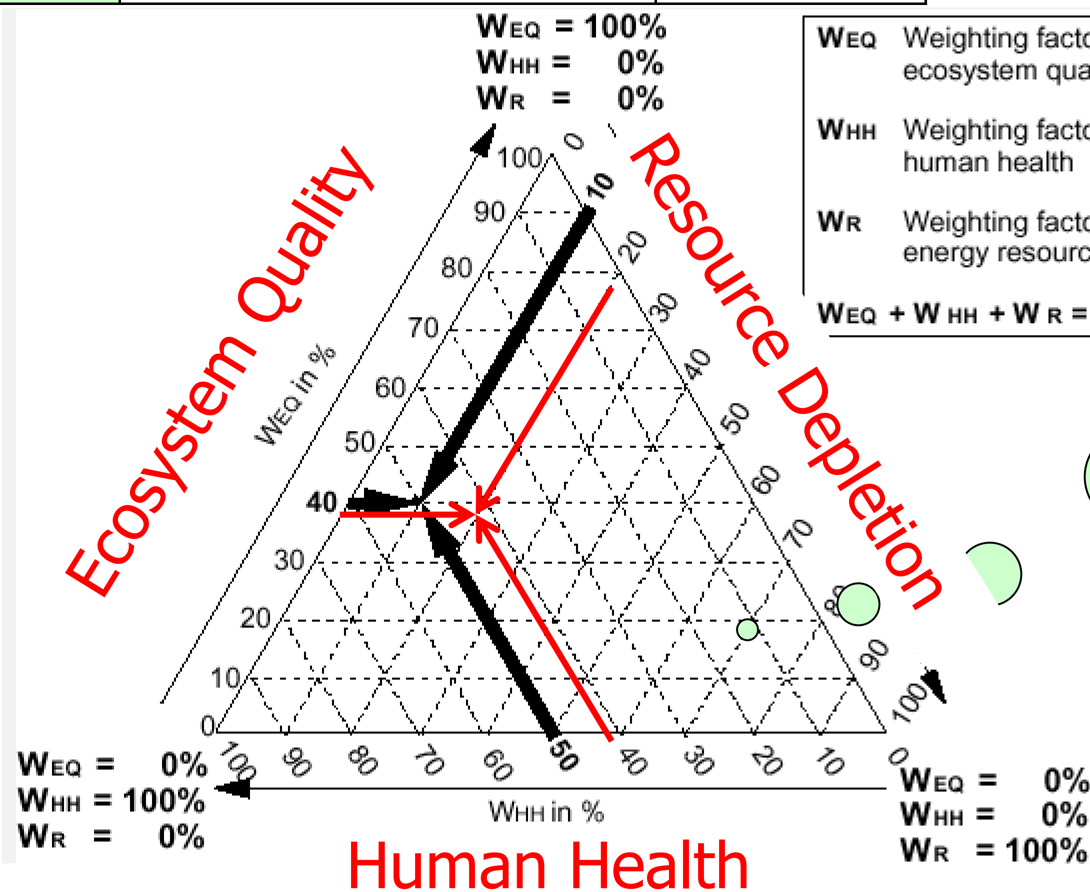
The difference among weighting methods depends on the specific application; the following example is related to the manufacturing of printed circuit boards:



LCA – ImA – Normalization – Mixing Triangle

Category	Normalization	Weight
Human Health	1,54 *10^-2	400
Ecosystem Quality	5,13 *10^3	400
Resource Depletion	8,41 *10^3	200

Eco-Indicator 99 - Hierarchist



W_{EQ}	Weighting factor for the damage to ecosystem quality
W_{HH}	Weighting factor for the damage to human health
W_R	Weighting factor for thedamage to energy resources

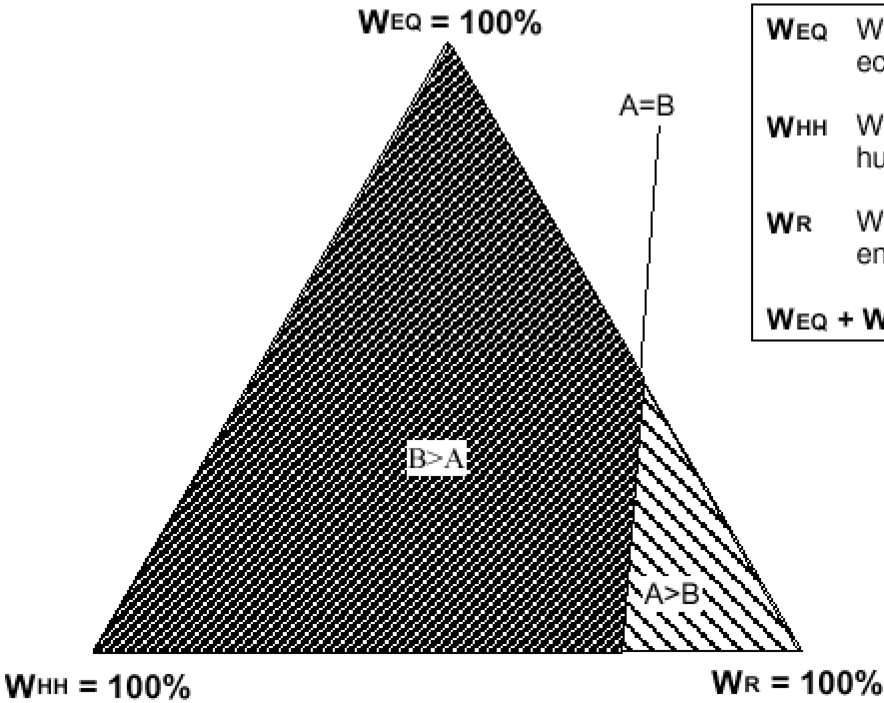
$W_{EQ} + W_{HH} + W_R = 100\%$

For all points within diagram the sum is 100%

Hierarchist:
400+400+200 =1000 Ecopoints

LCA- ImA - Mixing Triangle - Weighting

Mixing triangle



W_{EQ}	Weighting factor for the damage to ecosystem quality
W_{HH}	Weighting factor for the damage to human health
W_R	Weighting factor for the damage to energy resources

$W_{EQ} + W_{HH} + W_R = 100\%$

Eco-indicator' 99

The main feature of the Mixing Triangle is to establish lines of equal effect. These lines represent conditions for which products/processes A and B are environmentally equivalent.

The **Equal Effect lines** divide the Mixing Triangle into zones where A is better than B or viceversa.

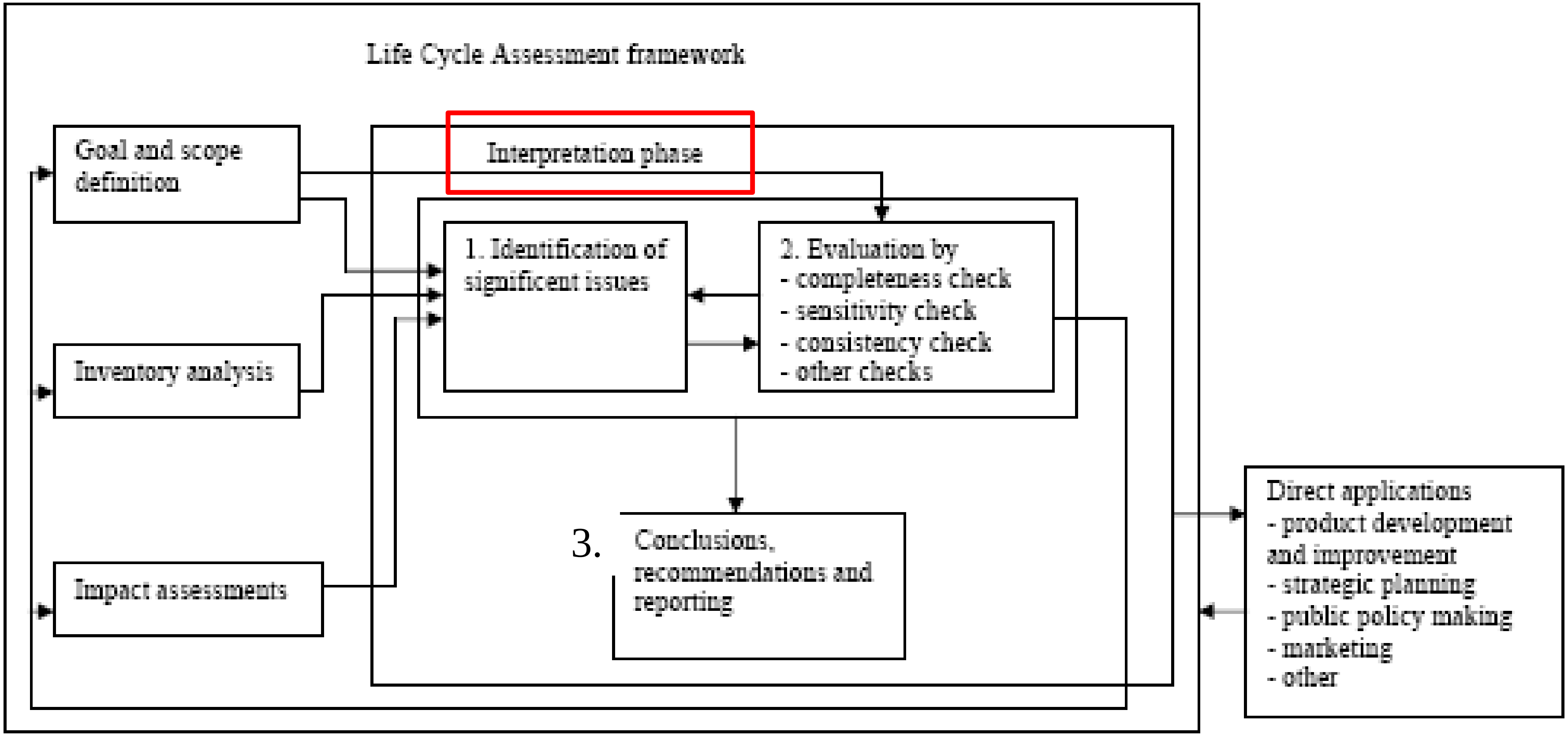
The mixing triangle is very useful in a LCA because it shows under which weighting conditions A would be better than B or viceversa.

The stakeholders must then agree what is a reasonablle weighting (consensus meeting). The matter is not establishing a truth but just making a reasonable choice.

LCA - Interpretation

The main elements of **Interpretation** are:

1. Identification of the significant issues of the Inventory (LCI) and Impact Assessment (LCIA) phases.
2. Evaluations about completeness of data; sensitivity of results to data uncertainty; consistency of results
3. Conclusions, recommendations and preparation of the final report



LCA – Interpretation – Significant Issues

The significant issues can be of different types; an example is shown in the following table.

Inventory data types	Impact categories	LCA stage
Energy Consumption	Resource use	Raw materials extraction
Emissions/air	GWP	Production
Emissions/liquids	Eutrophization	Transport
Solid Waste	Acidification	Disposal
....	Extinguished Species	....

LCA – Interpretation – Data Uncertainty

LCA Eng.xls

The **level which should be considered for significancy** must be clearly indicated. The table (example continued…) illustrates the issue of considering as significant only contributions larger than 0,05 or 0,01 Eco-points in Eco-indicator 99 for the product A-product-B case study.

Contributions lower than 0,01 EcoPoints are shaded in yellow.

Contributions lying between 0,01 and 0,05 EcoPoints are shaded in orange.

Non-shaded contributions are larger than 5%.

The Accuracy of the original data should be considered when evaluating the level to be considered for significancy.

Significant contributions **over 0,05 EcoPoints** are very few:

For product A:

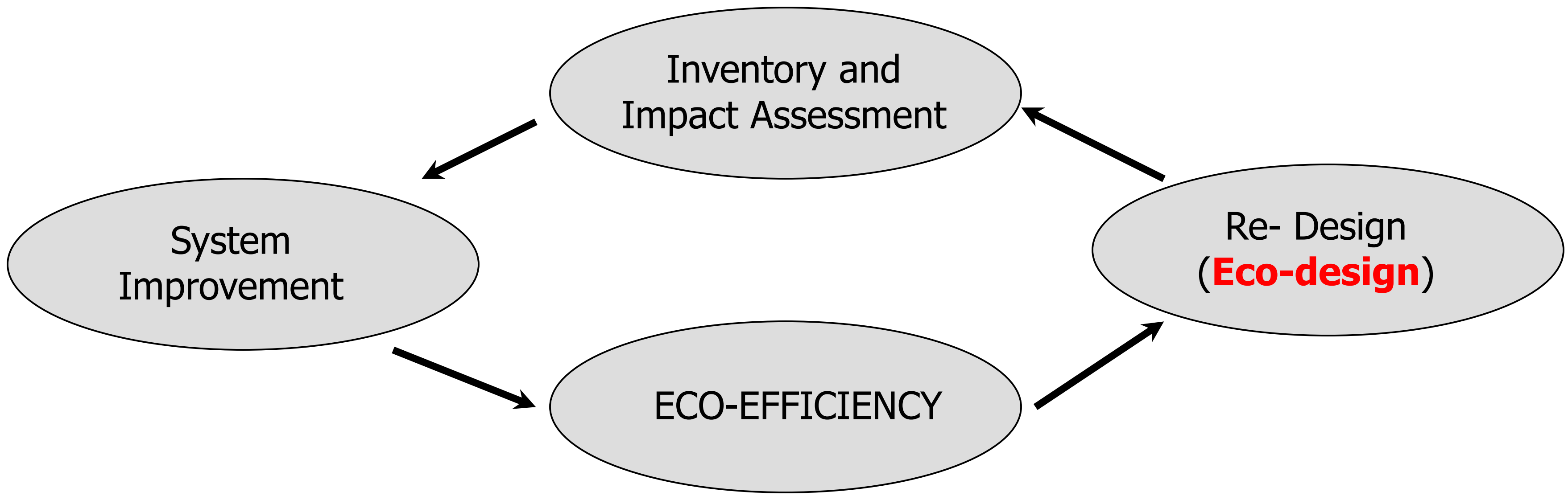
Oil, Cadmium, Hexachlorobenzene, Nickel, Copper

For Product B:

Hexachlorobenzene, Nickel, NO, Copper

Eco-99PointsA A	ECO-99PointsB B	Name
0,000000	0,006586	Natural Gas
0,793962	0,000000	Oil
0,000109	0,000109	Hard Coal
0,000513	0,000000	Lead Mineral Ore
0,005215	0,004575	Nickel Mineral Ore
0,011738	0,012634	Zinc Mineral Ore
0,811537	**0,023903**	**Resources Total**
0,032964	0,017122	Methylene Chloride
0,000899	0,000654	Methane
0,172243	0,000000	**Cadmium**
20,833248	13,129856	Hexachlorobenzene
0,120564	0,078336	Nickel
0,000050	0,000022	Formaldehyde
0,010167	0,013877	CO2
0,000002	0,000000	Chloroformium
0,000000	1,021082	NO
21,170137	**14,260949**	**Human Health Total**
0,212040	0,186960	Copper
0,035363	0,000000	Lead
0,036923	0,000000	**Cadmium**
0,000015	0,000000	Benzene
0,000000	0,008174	Pentachlorophenol
0,284341	**0,195134**	**Biodiversity Total**

LCA – Interpretation – Recommendations (Improvement)



Recommendations include proposals for improvement, describing possible actions for the improvement of the product/process.

These actions must be supported by evidence of environmental profitability (the LCA shows the most effective ways to solve problems).

ELCA (Exergy Life Cycle Analysis)

The use of **Exergy** has been proposed by several researchers as a powerful addition to LCA studies.

With specific reference to fossil fuels, exergy provides a **quantitative measure of the fraction of the chemical energy of the fuel which can be converted into work**; with reference to depletion of natural resources, the use of an energy or exergy unit [MJ] is already a standard in LCA for measuring the additional expense of extracting the raw materials.

The **Cumulative Exergy Consumption CExC** over the Life Cycle of a product, process or plant is a quantitative measure of efficiency and environmental sustainability.

Most modern LCA methods include the possibility of calculating CExC in parallel to other synthetic indicators.

CExC is anyway a global system/product/process indicator.

The Exergo-Environmental Analysis is a method which allows tracing back the global CExC or LCA score to system component performance, with an aim of optimization.

ELCA (Exergy Life Cycle Analysis)- 2 - Steps

Goal definition and scoping is identical in LCA and ELCA.

The **Inventory Analysis** is more complex for ELCA: in fact, differently from LCA, it is necessary to **close all materials and energy balances**, so that mass and energy are effectively conserved. This needs a complete description of all material and energy streams.

In order to perform an **Exergo-Environmental Analysis**, the LCI should be detailed and allocated to individual plant components (= elementary processes) in order to evaluate their environmental cost (= EcoPoints, weighted)

The **Impact Assessment** is simplified for ELCA (global): in fact, rather than estimating a set of different category indicators, it is only needed to calculate exergy of all the flows, and determining the exergy destruction over the complete life cycle for all sub-processes.

ELCA (Exergy Life Cycle Analysis)- 3 – Allocation Criteria

An **Allocation Criterion** must be applied when co-production of different products (e.g., Combined Heat and Power), recycling, or processes such as waste processing with production of electricity and/or heat are involved.

Three different **allocation criteria** are possible in practice with ELCA:

- **allocation of the CExC** to one or the other product **according to the exergy** of the different product flows

- **allocation of the CExC** to one or the other product according to the exergy destruction which would be encountered in the **separate production of each product in a reference plant** (to be defined according to the state-of-the-art)

- **Marginal cost method**, that is, allocation of the CExC within each stream of the plant **proportionally to the change in the exergy values of the flows**. Typically the analysis should start from elements, having zero reference exergy, and evaluate the marginal increase of exergy in the flows of materials according to exergy spent for their transformation.

Zero - ELCA (Exergy Life Cycle Analysis)- 4 - Emissions

How **emissions** are treated in ELCA?

The exergy value of these flows can be very small (both because of limited mass flows, and of the limited specific exergy of the flows).

The recommended approach is applying **Zero-ELCA**: that is, an Exergy Life Cycle Analysis completed with emissions treatment capable of reducing to zero (?) the emissions of the plant/process/product.
Emissions treatment equipment consumes large exergy amounts, because of the use of fuels, energy and chemicals: accounting this exergy flows, instead of using the simple physical/chemical exergy of the emissions, allows to estimate what would be - in terms of exergy expense – the environmental cost of emission treatment.

For many emissions it is difficult to identify a treatment process capable of reducing to zero the environmental effect: it is thus advisable to consider the reduction below a level commonly accepted for environmental sustainability.

LCA: Application to advanced energy systems (follows….)

LCA finds immediate applications in the calculation of the environmental costs of power generation.

When using fossil fuels, most of the environmental impact is found in the **operating phase**, rather than in the construction or decommissioning phases.

LCA provides powerful indicators for several relevant interaction modes with the environment

Example: LCA study of three different options for Carbon sequestration from power plants

(2001; EcoIndicator 95 = Midpoint)