Modul_2022

Ecodesign and Ecoinnovations

Nenad Zrnić // Miloš Đorđević

Ecodesign strategies and LCA

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ECO PRODUCT DESIGN STRATEGIES

INTRODUCTION

In order to design a better product (improved, i.e. higher performance and with less environmental impact), several problems need to be solved. The crucial thing for designers is to be properly and fully informed about the characteristics of materials, where they come from, whether they are renewable or not, what their mechanical characteristics are, how much processing effort do they require, how they are blended, whether they can be recycled, etc. The design of ECO PRODUCTS relies on DfX approach, with special emphasis on design from the aspect of environmental protection (DfE - Design for Environment). When designing ECO PRODUCTS by applying LCT (Life Cycle Thinking) and DfX approach, the following design aspects must be borne in mind:

_design for minimal use of materials,
_design for disassembly,
_design for recycling and use of recycled materials,
_design for remanufacture,
_design for the reduction of hazardous materials,
_design for energy efficiency,
_design to meet regulations and standards.

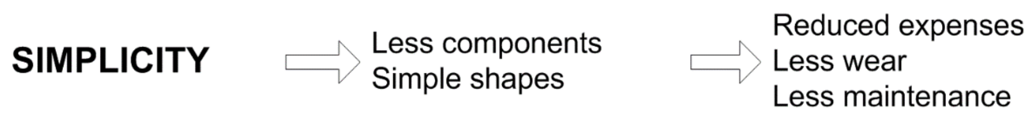
SO, WHAT HAS TO BE DONE?

As RAW MATERIAL SAVINGS are one of the MAIN GOALS of the DESIGNER, the following options must be considered:

_reduction of the amount of material,
_reduction of different types of materials,
_savings of raw materials through adequate use and reduction of wastes,
_rare or expensive materials should be replaced,
_reduction of the use of materials by reusing modules, assemblies or the entire product,
_reduction of the number of components = simpler product.

DESIGN FOR MINIMAL USE OF MATERIALS

Designers need to look for the solution that has the LOWEST NUMBER OF COMPONENTS WITH THE SIMPLEST SHAPES! During the embodiement phase, the main strategy should be to avoid unnecessary components!



1. Figure_Advantages of simplicity

MINIMIZATION OF RESOURCE UTILIZATION

Benefits from less resource usage:

_less use of resources requires less extraction of raw materials,
_less materials being processed, requires less energy,
_less energy needed for the transport of raw materials and products,
_as a consequence of the above, the levels of emissions and produced waste during the extraction and processing of raw materials, manufacture, transport and renewal of product components are lower.

SIMPLICITY

SIMPLICITY is one of the three principles in THE embodiement PHASE of design, [Pahl & Beitz, 1996]:

_simplicity,
_clarity,
_safety.

Simplicity generally guarantees economic feasibility. A small number of parts and basic forms will certainly be produced faster and easier with fewer resources (human, material, energy). In technology, the term simplicity refers to something that is not complex, “easy to understand or easy to make”. As a rule, the objective should be a consideration of a minimum number of sub-functions and a clear combination of them when the product function structure is defined.

SIMPLICITY OF FORM MEANS:

_geometric shapes, for which we can easily do stress and strain calculations,
_symmetrical shapes, which allow the identification of deformations during the technological process and/or due to the effect of mechanical or thermal loads.

SIMPLICITY IN PRODUCTION AND QUALITY CONTROL MEANS:

_geometric shapes that allow the use of established production methods, which saves the time needed to make the product,
_production processes involving short setup times and idle times,
_shapes that have been chosen to facilitate the inspection procedures.

SIMPLICITY IN ASSEMBLY PROCESSES MEANS:

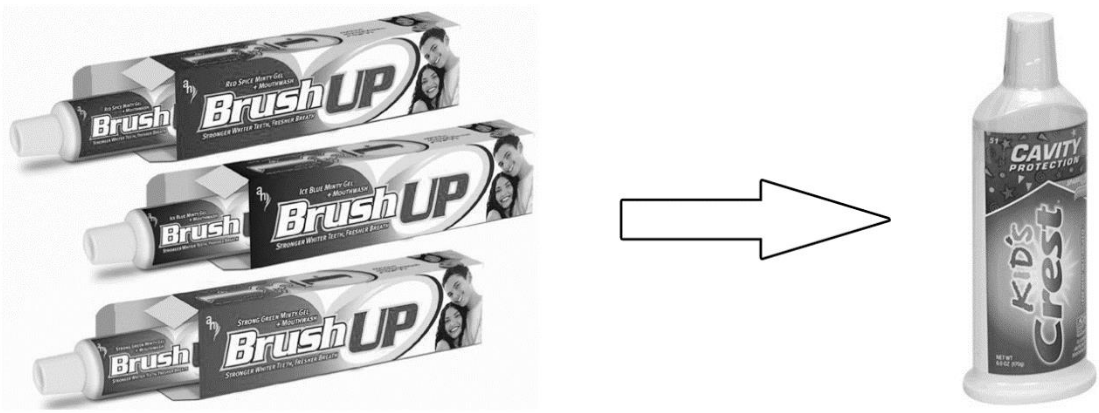
_easy identification of components to be assembled,
_that assembly instructions can be easily followed,
_the setup process is clear, precise and performed only once,
_reassembly of pre-assembled components should be avoided.

SIMPLICITY FOR RECYCLING IS REALIZED THROUGH:

_using recyclable materials,
_simple assembly and disassembly procedures,
_simplicity of the components.

SIMPLICITY IN PACKAGING (REDUCING THE NUMBER OF LAYERS):

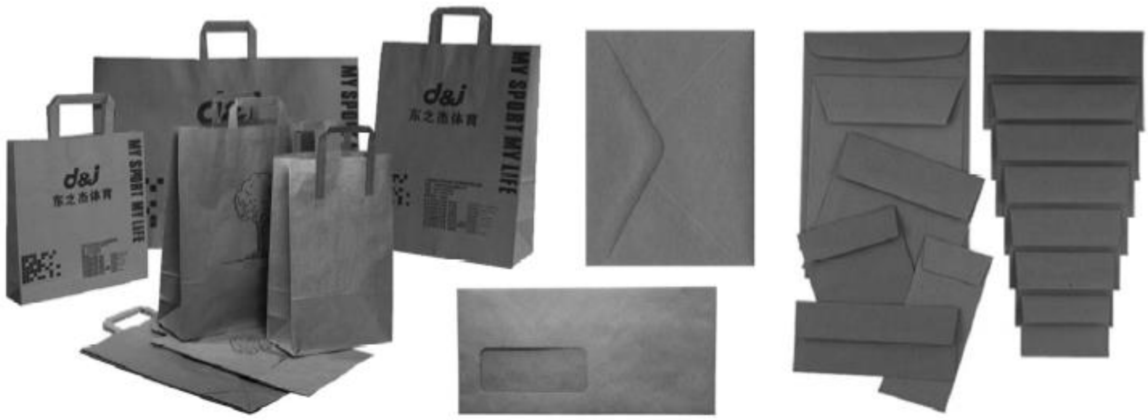
_the primary layer or packaging for consumption (e.g. soft drink bottles, toothpaste tube, flour bag),
_the secondary layer of the packaging is used to facilitate self-service, local transport or prevent stealing (e.g. 6-can packaging, packaging for multiple bottles of Coca-Cola with a holder, a box of toothpastes),
_the third layer of packaging is used for transport and distribution (e.g. cardboard boxes, pallets, metal container).



2. Figure_Example of reducing a single layer of packaging

Sometimes the designer is forced to CHANGE MATERIAL for some reasons (e.g. material is expensive, hazardous, etc.). This is a difficult task, because it is necessary for the designer to have all the data on both new and old material. Material change can lead to a better solution, taking into account both the material testing and the technological process, without risking the quality of the product and its performance. Examples of material change:

_water-based adhesives and inks,
_brown paper (unbleached),
_kraft paper for fast food packaging.



3. Figure_Examples of use of unbleached and kraft paper

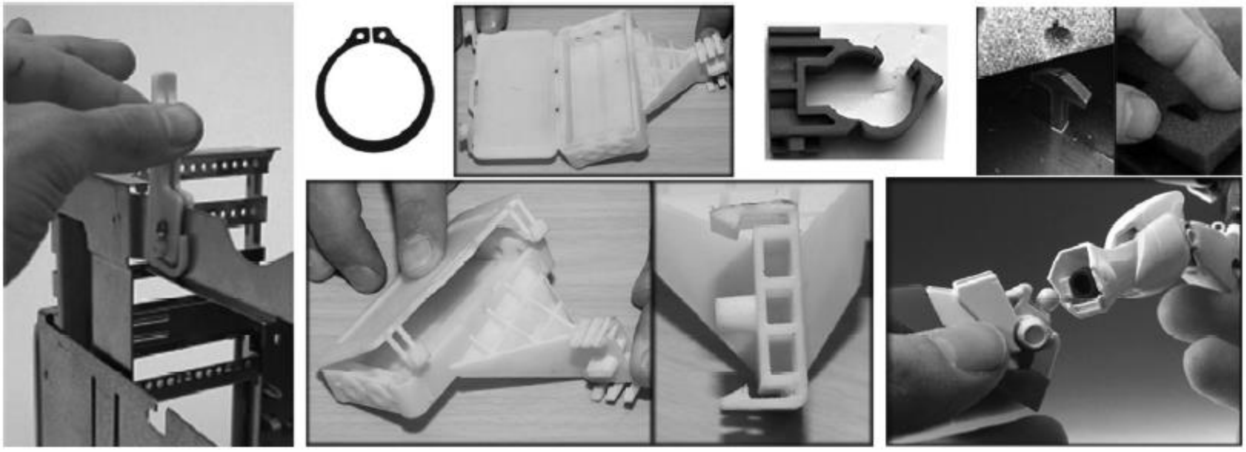
DESIGN FOR DISASSEMBLY (DfD)

DISASSEMBLY OF THE PRODUCT can be performed in the following ways:

_NON-DESTRUCTIVE - as a reverse assembly process,
_DESTRUCTIVE - by destroying the structure of the product.

Principles to facilitate disassembly:

_provide easy access to parts and fasteners without damaging the parts,
_modular product design,
_reduce the mass of individual parts and modules,
_use fastening and bonding techniques (ties, screws) instead of adhesives (bonding),
_reduce the number of breakable parts,
_design for easy assembly, to ensure easy reassembly,
_design to allow the use of standard hand tools for disassembly,
_design for easy alteration, which facilitates reprocessing of parts thus providing additional materials, as well as encompassing and adjustment characteristics.



4. Figure_Use of snap-fits in design for disassembly

DISASSEMBLY FOR RECYCLING

DISASSEMBLY FOR RECYCLING is carried out with the aim OF INCREASING THE RECOVERY, through selective separation of parts and materials. When designing products for SIMPLE DISASSEMBLY, consideration should be given to:

_disassembly process costs,
_benefits from reuse or recycling of components and materials,
_landfill disposal costs,
_environmental impact.

VDI 2243

The recommendations of the Association of German Engineers VDI 2243 contain a large number of instructions for DfD. According to them, three phases of recycling can be distinguished:

_recycling during production,
_recycling during use,
_recycling after the use of product (end-of-life).

The main OBJECTIVE OF RECYCLING DURING PRODUCTION is TO REDUCE THE AMOUNT OF WASTE and to recycle the waste material without adversely affecting the environment.

RECYCLING DURING THE USE of the product IS defined as REPARATION WITH THE AIM OF EXTENDING THE LIFE OF THE PRODUCT and consists of:

_disassembly,
_cleaning,
_inspection and sorting,
_restoration of components,
_reassembly.

RECYCLING AFTER THE USE OF PRODUCT (end-of-life) AIMS to recycle as much material as possible and TO INCREASE THE VALUE THAT CAN BE GAINED BY RECYCLING THE PRODUCT.

Recycling instructions are divided into 3 categories:

_selection of materials, with special instructions for plastics,
_selection of fasteners,
_structure of the product.

VDI 2243 GENERAL RECOMMENDATIONS FOR MATERIAL SELECTION

_reduce the number of different materials to a minimum,
_avoid the use of hazardous and toxic substances,
_parts containing hazardous substances should be clearly marked and simply disassembled,
_avoid the use of rare materials,
_parts and subassemblies connected inseparably shall be made of the same or compatible material,
_implement materials that can be recycled in existing recycling systems,
_use recycled materials,
_reduce the amount of material used - avoid oversizing,
_label the materials,
_reduce the packaging,
_reduce waste.

VDI 2243 RECOMMENDATIONS FOR PLASTICS

_use as few different plastics as possible,
_choose recyclable plastics (thermoplastic - e.g. PET, PS, HDPE...) and plastics that are compatible in terms of recycling,
_choose plastics that can be burned without the emission of hazardous substances,
_avoid PVC and polymers containing halogenated substances,
_avoid brominated combustion retardants,
_mark the combustion retardants or other additives used,
_plastic parts to be joined should be made of the same material,
_parts weighing more than 25 g shall be marked according to ISO 11 469,
_avoid incompatible labels on plastic products. It is preferable to imprint the markings into plastic,
_ensure the application of compatible inks when used on plastics,
_avoid painting or coating plastics,
_avoid metal inserts in plastic.

VDI 2243 RECOMMENDATIONS FOR THE SELECTION OF FASTENERS

_reduce the number of fasteners,
_use as few threaded and as many snap-fit fasteners as possible,
_reduce the number of tools required to remove fasteners. Use fasteners for which the same tool is used, in order to avoid changing the tool,
_allow access to fasteners on one side, in order to avoid turning the product,
_avoid the application of special tools (fasteners),
_fasteners should be removed simply,
_enable accessibility to the fasteners,
_snap-fit fasteners should be in visible places and should be disassembled with standard tools,
_if possible, use the fasteners made of a material compatible with the parts to be connected,
_if the two parts cannot be compatible, make them easily separated,
_avoid pressed connections with materials incompatible with iron or aluminum,
_do not use adhesive unless it is compatible with the materials of the parts to be joined,
_reduce to a minimum the number and length of cables and wires,
_breakable joints may be designed, instead of using fasteners,
_avoid chemical surface coating (electroplating, chrome plating...).

VDI 2243 RECOMMENDATIONS REGARDING PRODUCT STRUCTURE

_reduce the number of parts,
_apply a modular approach, with independent module functions, if possible,
_non-recyclable parts should be grouped so that they can be easily removed,
_place high-value parts in easily accessible places,
_provide easy access to parts that can be disassembled without damage and reused,
_parts that must be removed before processing or disposal (batteries, mercury contacts, LCD monitors..) must be in visible places and easily removable,
_parts with high recyclable potential must be easily accessible, close to the surface or edges, so that they can be broken off,
_avoid metal parts covered with resin or reinforcement in plastic,
_access points or breaking points should be obvious,
_make the disassembly instructions readily available (Internet, etc.). The drawings must contain information on parts containing hazardous substances and parts that have a high potential for recycling.

ADDITIONAL MATERIAL SELECTION INSTRUCTIONS

The following recommendations should be followed when recycling metal parts:

_not-coated materials are recycled more easily than coated materials,
_less alloyed metals are more easily recycled than more alloyed materials,
_most cast irons are easily recyclable,

_aluminum and magnesium alloys and car steel can be separated and recycled after crushing in shredders,
_impurities in steel (Cu, Sn, Zn, Pb or Al) reduce recyclability,
_impurities in aluminium (Fe, steel, Cd, Sn, Pb) reduce recyclability,
_reduction of the number of different materials is desirable in terms of collection, storage, recycling...

NEW TYPES OF FASTENERS

New types of fasteners include:

_alloys and polymers that “remember” the shape,
_joints that are self-disassembled when heat is applied, etc.
_quarter-turn threaded fasteners,
_specific construction of snap-fit joints,
_points provided for breakage.

APPLICATION OF “SMART” MATERIALS IN FASTENERS

By applying simply dismantlable joints made of a “SMART ALLOY” (Shape Memory Alloy – SMA, or Shape Memory Polymer- SMP), disassembly is reduced to heating the product and then cooling, whereby the PRODUCT ITSELF BREAKS DOWN INTO PARTS, due to the loosening of joints. In doing so, IT DOES NOT MATTER WHETHER THE JOINTS ARE EASILY ACCESSIBLE OR NOT[1].

Among the best-known alloys of this type is Nitinol, a nickel-titanium alloy (50% Ni, 50% Ti). This alloy has two unique properties:

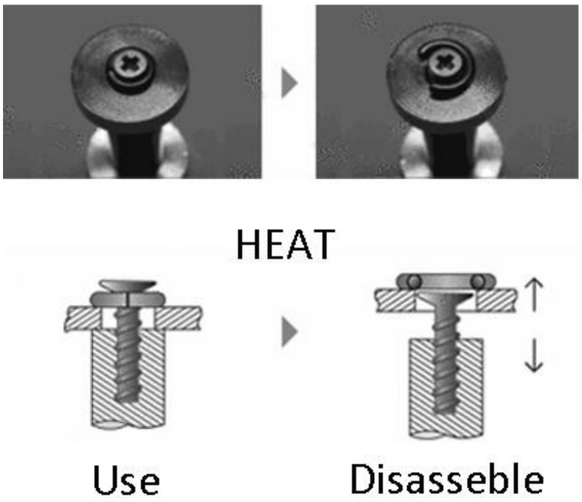
_the ability to “MEMORIZE” THE SHAPE, and
_SUPERELASTICITY (pseudoplasticity).

Shape memory is the ability of nitinol to undergo deformation at one temperature, stay in its deformed shape when the external force is removed, then recover its original, undeformed shape upon heating above its "transformation temperature".

Superelasticity is the ability for the metal to undergo large deformations and immediately return to its undeformed shape upon removal of the external load. Nitinol can deform 10–30 times as much as ordinary metals and return to its original shape. Superelasticity occurs in a narrow temperature range slightly above the transformation temperature. Whether nitinol behaves with the shape memory effect or superelasticity depends on whether it is above the transformation temperature of the specific alloy. Below the transformation temperature it exhibits the shape memory effect, and above that temperature it behaves superelastically. Due to its BIOCOMPATIBLE characteristics and HIGH CORROSIVE RESISTANCE

[1] *Alloys that “remember” the shape have their application in DfA and DfD approaches. See Jacques Fresco – Utopia (http://www.youtube.com/watch?v=BpyBwPQNyVU).*

(higher than for stainless steel) it is often used in medicine (stents and orthopaedic implants) and dentistry (dentures). It's also used to make sensors, heat engines and cell phones...



5. Figure_Disassembly by heating the component with screw connection and Nitinol washer (left) and Nitinol stent after heating (right)

The biggest limitations of the use of Nitinol are very difficult casting and processing and alloy production, as well as welding, which requires special procedures.

The latest research related to materials that “memorize” the shape concerns the MULTI-MEMORY TECHNOLOGY, with the aim of obtaining IMPROVED STRUCTURES (devices) that “memorize” the shape.

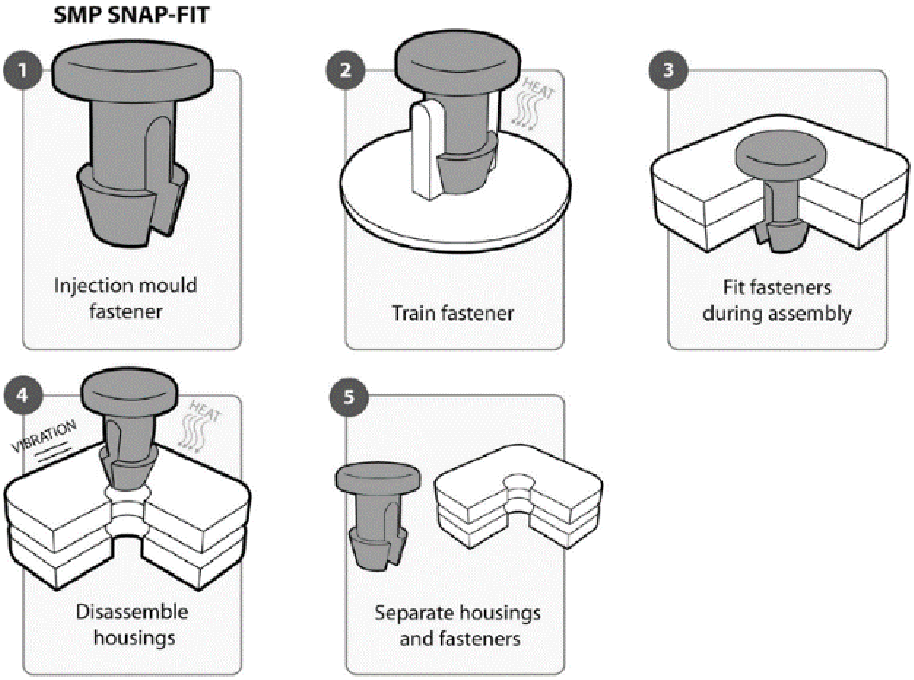
QUARTER-TURN FASTENERS

This type of joint achieves significant savings in assembly/disassembly time, especially when it comes to joints that are more often separated and reconnected (e.g. for fastening the side covers of the desktop computer housing).

6._Figure Quarter-turn fasteners

SPECIFIC STRUCTURE OF SNAP-FIT JOINTS (HOOKS)

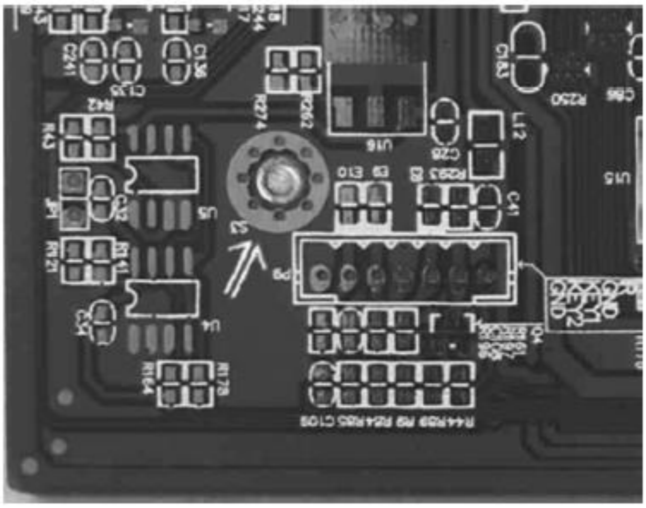
The specific structure of the snap-fit joints, which are disassembled by heating and applying vibrations is shown below. Such joints are designed using Finite Element Method - FEM, and this example, specifically, is also characterized by the use of "smart" material, of which the snap-fit fastener is made.



7. Figure_ Specific structure of SMP snap-fit joints [Source: Gray and Jones, 2008]

BREAKAGE POINTS (DESTRUCTIVE DISASSEMBLY)

Another form of new types of joints, or rather the principle, is the application of small perforations around the joint and thus the formation of intended points for breakage, i.e. destructive disassembly. This is applied with the aim of saving disassembly time. The joints themselves in this case are made as inseparable (e.g. by riveting, or by sealing with plastic).



8. Figure_ Breakage points – small perforations formed around an inseparable connection

CRITERIA FOR MANUAL AND MECHANICAL DISASSEMBLY

When designing for MANUAL DISASSEMBLY, attention should be paid to the easy separation of joints as well as separation and sorting of materials, since the primary limiting factor for manual disassembly is the TIME spent by the worker on the separation of parts. Thus, the TIME REQUIRED FOR DISASSEMBLY IS THE BASIC CRITERION FOR THE APPLICATION OF MANUAL DISASSEMBLY.

When designing for MECHANICAL DISASSEMBLY, care should be taken that the product can be QUICKLY AND EASILY SEPARATED INTO CLEAN MATERIALS according to their properties, after crushing. The time required for disassembly of joints and marking the materials of the parts are not of importance for mechanical disassembly, while the choice of materials is of crucial importance. THE BASIC CRITERION FOR MECHANICAL DISASSEMBLY IS THE PERCENTAGE CONTENT OF METAL.

MANUAL DISASSEMBLY

TOOL SELECTION

Table 1: Use of tools depending on type of joint and problems encountered during disassembly [Source: Kandikjan, 2006]

Type of fastener	Disassembly tool	Problems in disassembly
Screw	Screwdriver (manual or battery-powered)	Corrosion, damage, access
Bolt and nut	Screwdriver, wrench, hexagonal head socket ratchet	Access, damage, corrosion, missing parts
Rivets	Chisel, hammer, grinder, cutter, burner	Complexity, corrosion, access
Stapler	Stapler pliers, flat screwdriver	Access, corrosion
Retaining ring	Retaining ring pliers	Access
Fastening snap-fits	Pliers, screwdriver, cutter	Access, corrosion
Cantilever hook	Pliers, screwdriver, cutter	Access, complexity of most hooks
Weld	Chisel, hammer, burner, grinder	Complexity, damage to parts
Joint by plastic deformation	Pliers, hammer, cutter, circular saw	Complexity, damage to parts
Patent	Manual, pliers	Self-welding
Adhesive tape	Manual	Complications, stickiness, degradation, impurity

Disassembly tools are selected according to the following criteria:

_choose a tool that corresponds to the type of fasteners,
_choose a tool that minimizes the time and cost of disassembly,
_choose a tool that can access the joint.

DISASSEMBLY OPERATIONS AND TIMES

The disassembly time can be determined in two ways:

_by measuring the disassembly time,
_by prediction based on previous knowledge and description of the types of joints according to the technical drawings.

Table 2: Loose parts removal time in seconds [Source: Kandikjan, 2006]

Degrees of freedom	Horizontal removal		Vertical removal	
	Using one hand	Using two hands	Using one hand	Using two hands
≥ 2	0.3	0.5	0.6	1
1	0.5	2	1	2.5

Table 3: One turn unscrewing time for screw joints [Source: Kandikjan, 2006]

	Hand tool [s]	Electric tool [s]
Unscrewing the screw for 1 turn	0.6	0.15

Table 4: Time required to remove retaining ring [Source: Kandikjan, 2006]

Removing retaining ring	Time [s]
Manual	1.5
By tool	3

Table 5: Time required for breakage [Source: Kandikjan, 2006]

Breaking	Time [s]
Using one hand	3
Using two hands	1
By tool	2

Table 6: Time required for cable and wire cutting [Source: Kandikjan, 2006]

	Power cable	**Wire**
Cutting [s]	0.5	0.25

Table 7: Time required to disconnect the connector [Source: Kandikjan, 2006]

Disconnecting	**Time [s]**
Manual	1.5

Table 8: Added time in [s] for unscrewing the bolt when encountering the obstacles and difficulties during disassembly [Source: Kandikjan, 2006]

	LD 1	**LD 2**	**LD 3**	**LD 4**	**LD 5**
UD 1	0	3	9	12	17
UD 2	6	9	15	18	23
UD 3	9	12	18	21	26

LEVEL OF DIFFICULTY:

LD 1 – easy access

LD 2 – moving in multiple directions to get around obstacles

LD 3 – limited visibility

LD 4 – far to reach

LD 5 – significantly difficult access

UNSCREWING DIFFICULTIES:

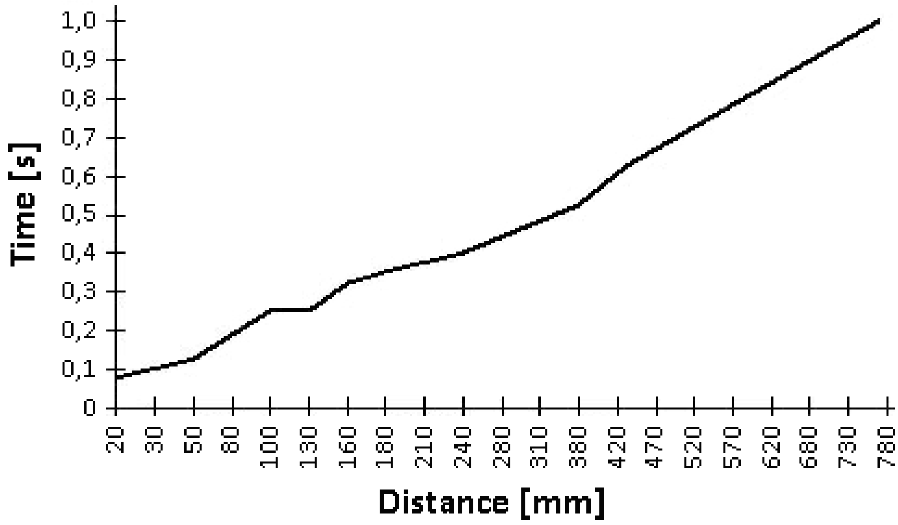
UD 1 – worn head

UD 2 – holding the part while unscrewing the screw

UD 3 – corrosion

PICKING UP AND RETURNING TOOLS: these times can also be used as times for sorting, i.e. putting disassembled parts into storage boxes.

TOOL CHANGE TAKES APPROXIMATELY 0.15 s.



9. Figure_ Dependence of disassembly time and relative distance of joints and tools diagram [Source: Kandikjan, 2006]

CALCULATION OF TIME AND COSTS OF DISASSEMBLY

The time required to perform the disassembly operation is calculated according to the following formula (on the example of a screw-type joint):

$$T_D = T_1 + n_z \cdot (T_2 + T_3 + T_4 + T_5) + T_6$$

where:

T_D – time for disassembly,

T_1 – tool pick-up time,

T_2 – time of bringing the tool to the screw,

T_3 – tool positioning time,

T_4 – tool application time,

T_5 – tool removal time,

T_6 – tool put-down time,

n_Z – number of screws.

The time of the entire disassembly operation is multiplied by the LABOR COST - C_l. Thus the COST OF MANUAL DISASSEMBLY - C_{MD} is obtained:

$$C_{MD} = C_l \cdot T_D$$

EXAMPLES OF DISASSEMBLY OF WORN-OUT HOME APPLIANCES

The following two examples can be used to estimate the time of disassembly and determine the purchase price (in North Macedonian denar) of worn-out products. STUDIES WERE CONDUCTED IN NORTH MACEDONIA: TATJANA KANDIKJAN, “EKO-CIRKON”, SKOPJE, 2006.

Disassembly was performed:

_by a qualified worker,
_the exact time of individual operations was measured,
_manual destructive disassembly with a burner was applied,
_these two products are 20 years old each and are not designed for easy disassembly.

EXAMPLE: DISHWASHER

10. Figure_ Manual disassembly of the dishwasher [Source: Kandikjan, 2006]

Table 9: Required dishwasher data [Source: Kandikjan, 2006]

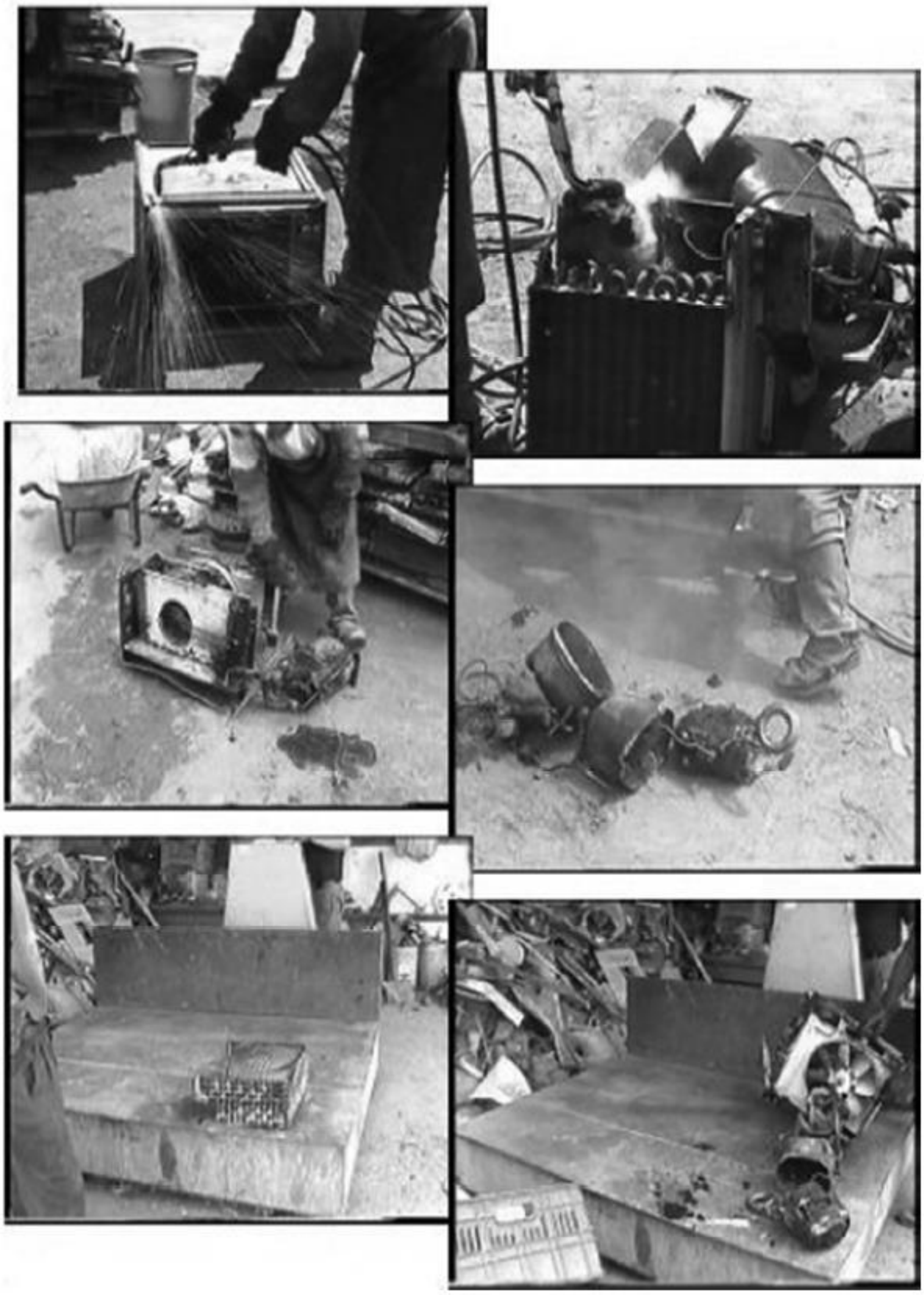
DISHWASHER	Iron	Stainless steel
Material contents	14 kg	10 kg
Purchase price of secondary materials	MKD 5/kg	MKD 25/kg
Adopted disassembly cost	MKD 1000/h	
Total disassembly time	< 10 min	

DISHWASHER PURCHASE PRICE (VALUE OF THE WORN-OUT DISHWASHER - V_M) is obtained when the cost of disassembly is deducted from the purchase price of separated materials:

$$V_M = C_{mat} - C_{MD} = (m_{Fe} \cdot C_{Fe} + m_{SS} \cdot C_{SS}) - C_I \cdot T_D$$

$$V_M = (14 \cdot 5 + 10 \cdot 25) - 1{,}000 \cdot 10/60 = \text{MKD } 153$$

EXAMPLE: AIR-CONDITIONER



11. Figure_ Manual disassembly of the air-conditioner [Source: Kandikjan, 2006]

Table 10: Required air-conditioner data [Source: Kandikjan, 2006]

Air-conditioner	**Iron**	**Copper alloy**
Material contents	38 kg	13 kg
Purchase price of secondary materials	MKD 5/kg	MKD 45/kg
Adopted disassembly cost	MKD 1000/h	
Total disassembly time	9.5 min	

AIR-CONDITIONER PURCHASE PRICE (VALUE OF THE WORN OUT AIR-CONDITIONER - V_M) is obtained when the price of disassembly is deducted from the air-conditioner purchase price:

$$V_M = C_{mat} - C_{MD} = (m_{Fe} \cdot C_{Fe} + m_{Cu} \cdot C_{Cu}) - C_I \cdot T_D$$

$$V_M = (38 \cdot 5 + 13 \cdot 45) - 1{,}000 \cdot 9.5/60 = \text{MKD } 516$$

THE COST OF REMOVAL OF FREON by an authorized person is MKD 300-500 per product. This reduces the purchase price to MKD 200-300.

MECHANICAL DISASSEMBLY

In the process of material recovery in which mechanical disassembly is used, the ENTIRE AMOUNT OF METAL IS NOT RECOVERED, because part of the metal is removed unseparated and attached to other materials that are left over after crushing. WHEN PERFORMING MECHANICAL DISASSEMBLY, THE PERCENTAGE CONTENT OF METAL IS TAKEN AS A CRITERION FOR ITS APPLICATION!

Table 11: Degree of metal recovery in the recycling process [Source: Kandikjan, 2006]

Metal	**Recovery percentage**	**Degree of purity**
Ferrous metals	90%	95%
Aluminum	80%	90%
Copper	95%	100%
Gold	95%	100%
Silver	90%	100%
Palladium	92%	100%

The value of the worn-out product (V_M) is determined as follows:

$$V_M = G_{rec} \cdot V - G_t \cdot C$$

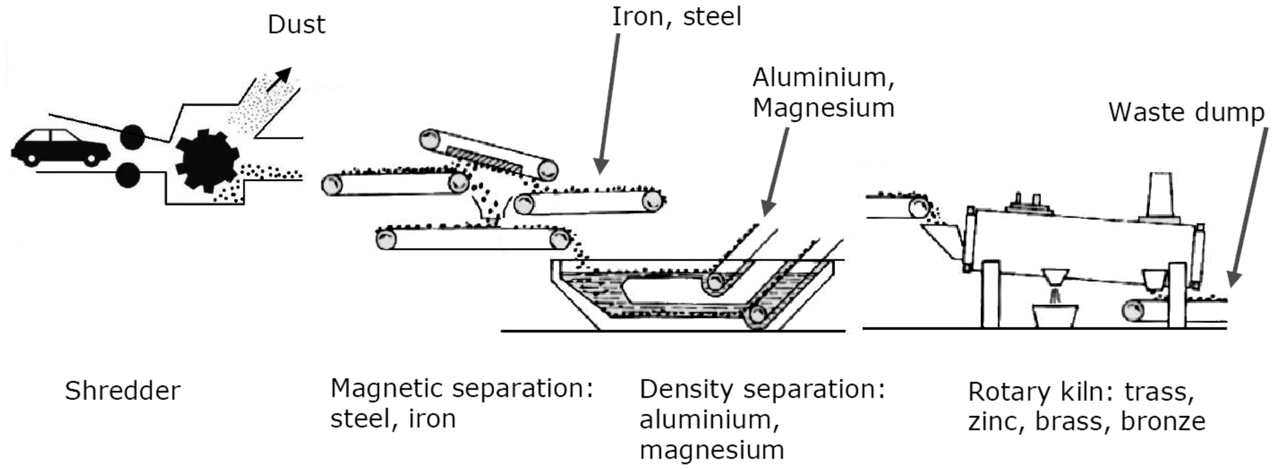
G_{rec} – weight of recyclable content of the product,

V – the price of separated secondary material,

G_t – total weight of the product,

C – the cost of crushing and separating a kilogram of material.

EXAMPLE: MECHANICAL DISASSEMBLY AND RECYCLING OF VEHICLES



12. Figure_ Mechanical disassembly of vehicle [Source: Bârsan, 2007]

DISCUSSION AND EXAMPLES OF DFD

Since most materials have little value as secondary raw materials, IT IS VERY IMPORTANT TO KEEP THE COST OF DISASSEMBLY AS LOW AS POSSIBLE, in order to profit from disassembly. Below are presented some examples of design simplification from a disassembly point of view and various principles applied.

EXAMPLE: UNIFICATION OF MATERIALS

The complete control panel of the CANDY washing machine is made of one type of plastic.

13. Figure_ Example of unification of materials

EXAMPLE: REPLACEMENT OF SCREW JOINTS AND DISASSEMBLY WITHOUT THE USE OF TOOLS

On the wristwatch shown in Figure 14, left, the screw joints were replaced by snap-fit fasteners and thus a simpler design and a reduced number of parts were achieved. Disassembly without the use of tools (portable computer shown in Figure 14, right) is one of the extreme achievements of the design for disassembly.

14. Figure_ Screw joints in the wristwatch were replaced by snap-fits (left), laptop disassembly is performed without using a tool (right)

DESIGN FOR REDUCTION OF HAZARDOUS SUBSTANCES

Table 12: Overview of battery use and toxicity [Source: EHSO, 2010]

Battery type	Size	Examples of use	Toxicity	Method of disposal
Alkaline (manganese)	**AAA, AA, C, D, 6V, 9V**	Flashlights, toys, clocks, smoke detectors, remote controls	non-hazardous waste	**M**unicipal **S**olid **W**aste - **MSW**
Button cells (mercury oxide, silver oxide, lithium, alkaline, zinc-air)	Size varies	Clocks, remote controls, hearing aids, toys, music cards	hazardous waste	households hazardous waste collection centres
Zinc-carbon	**AAA, AA, C, D, 6V, 9V**	Flashlights, toys, clocks, smoke detectors, remote controls, radio transistors	non-hazardous waste	**MSW**
Lithium-ion	**3V, 6V,** **3V** button	Cameras, calculators, computer motherboards	non-hazardous waste	recycling centres
Nickel-cadmium (rechargeable)	**AAA, AA, C, D, 6V, 9V**	Flashlights, toys, mobile phones, power tools, portable computers	hazardous waste	households hazardous waste collection centres
Nickel-metal hydride (rechargeable)	**AAA, AA, C, D, 6V, 9V**	Flashlights, toys, mobile phones, power tools, portable computers	non-hazardous waste	**MSW** and recycling centres
Alkaline manganese (rechargeable)	**AAA, AA, C, D**	Flashlights, toys, clocks, radios, calculators, remote controls	non-hazardous waste	**MSW**
Sealed lead acid (rechargeable)	**2V, 6V, 12V**	Video cameras, power tools, metal detectors, electric carts, cameras, clocks	hazardous waste	households hazardous waste collection centres
Lead-acid (car battery)	**6V, 12V**	Vehicles	hazardous waste	return to the distributor or recycling center
Silver oxide	Size varies	Clocks, toys, hearing aids, music cards, remote controls	hazardous waste	hazardous waste collection and recycling centres

Hazardous materials are those that:

_have a toxic effect on humans and other living things,
_are flammable, explosive or corrosive,
_deplete the ozone layer (ODS – Ozone Depleting Substances),
_contribute to global warming (GHG – Greenhouse Gases).

Products should be designed for safe disposal at the end of their life, and those containing toxic substances should be properly labelled with disposal instructions (decontamination, neutralization, etc.).

The most significant EU directives regarding electrical and electronic equipment and waste of this type are RoHS and WEEE. The need to reduce hazardous materials and increase the recycling of electrical and electronic equipment to protect human health and the environment prompted the EU to adopt these two directives.

In addition to these, the BATTERIES AND ACCUMULATORS DIRECTIVE - 91/157/EEC, is of great importance. The classification of batteries regarding toxicity is given in Table 12.

DESIGN FOR REUSE

15. Figure_Some examples of product reuse

The design for RE-USE is applied with the aim of obtaining a durable product, which can be used repeatedly for the same or different purpose (e.g. beer bottles), instead of being DISPOSABLE (discarded after a single use).

Reuse of the product before recycling or disposal can save:

_natural resources,
_energy,
_the need for disposal,
_costs.

DESIGN FOR REMANUFACTURE

REMANUFACTURE is the process of disassembly of used items, inspection and repair of components and their use in the production of new products.

Used products and components can be recovered to a state of performance similar to that of the new product. This activity is called REMANUFACTURE and results IN EXTENSION OF SERVICE LIFE. If remanufacture is impossible, at least some of the components can be recycled. If this is not possible either, the product is disposed of in a landfill.

16. Figure_Disposable camera, designed for remanufacture

In order to remanufacture the product, the following steps must be carried out (the importance of design for assembly and design for disassembly, which can reduce the cost of remanufacture, is great):

_DISASSEMBLY (product is disassembled, parts are cleaned),
_RESTORING some components and replacing others that cannot be repaired,
_REASSEMBLY (the product is considered to work as new!).

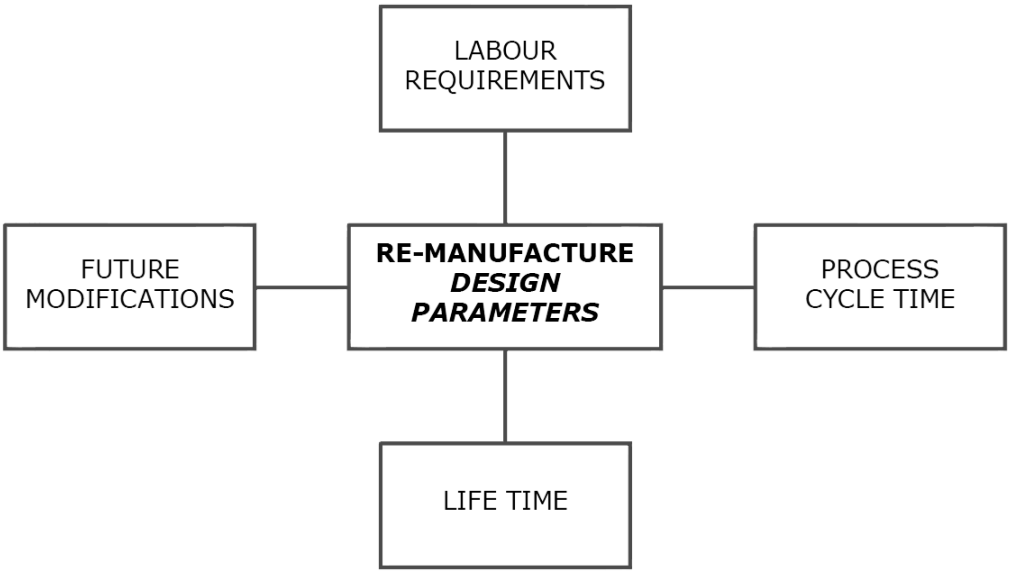
Aspects of remanufacturing must be observed in the product development process and at an early stage of design. Such requirements change the traditional product development process. In remanufacturing, the process begins with DISASSEMBLY, and continues with the INSPECTION and REPAIR of components and their use in the production of a new product.

Product is considered to be REMANUFACTURED if its basic components come from an already used product. However, the remanufactured product does not necessarily have to be identical to the product used.

Remanufacturing is widely used in commercial products (photocopiers), but is rarely used for electrical and electronic products in households. THE MOTIVATION for remanufacturing in household appliances is relatively low (not common) because:

_there is no centralised market and supply of such goods,
_rapid changes in technologies (e.g. computers),
_high transport costs,
_customers do not like “second-hand” products.

Regarding household appliances, the remanufacturing tendency is mostly observed in the field of power tools, vacuum cleaners, garden equipment, leisure and recreational equipment.



17. Figure_Remanufacture incentives

The design parameters, which have an incentive effect on the remanufacturing process, are:

_minimizing the direct labor requirements of disassembly/reassembly,
_minimizing the disassembly/reassembly process time,
_maximizing the lifespan of parts that are not new,
_maximizing the simplicity of future modifications.

When it comes to remanufacture, RESIDUAL VALUE has great significance and impact. The notion of residual value is easiest to explain through an example:

The company owns a machine purchased for €20,000. This machine has just come to the end of a useful life (of 5 years). The company knows that if it sells the machine now, it will be able to recover 10% of the money for which the machine was purchased.

Therefore, the RESIDUAL VALUE of the machine would be: 0.1 · 20,000 = €2,000.

The advantages of remanufacture are as follows:

_increasing the number of products and services using remanufactured components,
_price reduction by about 50% to 70% in relation to the new product,
_increase in residual value,
_renewed quantities and extension of the life cycle of the product,
_environmental protection and entrepreneurship will find common interest in remanufacture: pollution prevention and higher corporate profits,
_equipment users will not care whether they use a new or remanufactured product, as long as they get the expected usefulness and reliability of the product.

DESIGN FOR RECYCLING – DfR

THE DESIGN OF PRODUCTS FOR RECYCLING is a form of design STRATEGY, which takes into account the ecological criterion with the aim of:

_USE OF RECYCLED MATERIALS in the production of new products (production phase),
_FACILITATING THE RECYCLING OF PRODUCTS at the end of their service life (EoL phase).

In order to achieve the objectives of the DESIGN FOR RECYCLING, two basic requirements must be met:

_ELIMINATE OR REDUCE THE USE OF HARMFUL OR TOXIC MATERIALS, which may pose a serious hazard to the environment, or endanger the workspace of recycling workers,
_DISCOURAGE THE USE OF NON-RECYCLABLE MATERIALS and MANUFACTURING TECHNIQUES that produce non-recyclable products using current technologies.

Products are easier to recycle if they are appropriately designed. Except for mono-materials (plastic bags, aluminum cans, etc.), recycling begins by DISASSEMBLY the product, which is achieved either by reverse process from assembly (NON-DESTRUCTIVE DISASSEMBLY), or BY CUTTING it into pieces - fragmentation (DESTRUCTIVE DISASSEMBLY). Disassembly should be considered at the embodiment stage of design. Difficult and expensive disassembly does not contribute to recycling, especially if the cost of disassembly outweighs the profit from recycling. The product should be designed to be dismantled rather than destroyed. At best, after disassembly of the product, the materials are separated and compacted into bundles, in order to facilitate transport to the recycling plant. However, most often the separation of unseparated waste is carried out in special plants, where manual separation is combined with mechanical systems.

The key items to pay attention to when designing for recycle are:

_replacement of primary materials with recycled materials,
_reuse of parts and components,
_use of as few different materials as possible,
_elimination of toxic and hazardous products,
_modular design, easy to disassemble,
_identification of parts by coding (as in the automotive industry),
_use of compatible materials (do not mix materials that cannot be separated/disassembled; e.g. metal structures cast in plastic).

A list of useful instructions for the recycling process should include:

_that the product, once withdrawn from use, can be safely and economically recycled using existing recycling technologies and methods,
_that the product can be recycled WITHOUT CAUSING A RISK TO HUMAN HEALTH OR THE ENVIRONMENT due to hazardous (harmful) ingredients,
_that IF THE RECYCLING OF THE PRODUCT PRESENTS AN ENVIRONMENTAL RISK and is not economical, the product SHOULD NOT BE SOLD without changes in design or production, which will eliminate that risk,
_that for some applications it MAY NOT BE FEASIBLE TO REPLACE HAZARDOUS SUBSTANCES in components by other less harmful ones; in these cases, there should be new COOPERATION BETWEEN THE MANUFACTURER AND THE RECYCLER, in order to reduce the risk from the recycling process for workers and the environment.

Designers play a key role in recycling. Each stage of the product life cycle can be explained through the perspective of the waste manipulation hierarchy (prevention pyramid).

RAW MATERIALS STAGE

DESIGN:

_compliance with laws and directives,
_ECO-LABELS show compliance with international environmental expectations and “green” procurement criteria,
_use of recycled material, whenever possible,
_design for facilitated disassembly and recycling.

MATERIAL SELECTION

_use recycled materials and reduce the use of raw materials,
_reduction of the number of different materials used in the product potentially adds value to the product at the end of its life cycle,
_reducing the size of the product reduces the consumption of resources,
_eliminate or reduce the use of prohibited substances.

MANUFACTURING STAGE

_avoid the need to use harmful and prohibited materials in the production process,
_optimize assembly in the production process (it is directly related to disassembly, DfA, DfM, DfD),
_avoid processes with high energy consumption in production (e.g. multiple heating and cooling cycles),
_minimize waste generation in the production process (avoid excess coatings, cuttings, shortenings, by-products).

DISTRIBUTION STAGE

PACKAGING:

_better packaging design reduces the impact of the product on the environment, quantity and costs of packaging.

TRANSPORT:

_smaller, lighter products reduce CO_2 emissions, the impact of transport on the environment and costs.

USE STAGE

The product must be designed in accordance with the following principles:

_simple disassembly for repair, upgrade or reuse,
_it does not contain disposable components, such as disposable cartridges, containers, or batteries,
_uses electricity efficiently, and/or uses renewable energy sources,
_uses batteries that are easily identifiable by type and are removable.

END-OF-LIFE (EoL) STAGE

The main objective of this stage is to facilitate the reuse and recycling of products, so that recycled materials can be used rather as resources than end up as expensive waste.

DESIGN FOR ENERGY EFFICIENCY

By increasing ENERGY EFFICIENCY[2] and using energy sources with minimal impact on the environment, resource consumption, soil, water and air pollution can be reduced, while enabling production savings.

THE DESIGN FOR MINIMUM CONSUMPTION involves the following strategies:

_designing products with minimal use of special materials (e.g. recycled water for washing machines),
_offering optimal support to consumers when replacing consumables (e.g. cartridge refill option instead of purchasing a new one),
_defining whether consumables can be replaced with reusable ones (e.g. vacuum cleaner filters, coffee machine filters).

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[2] *The ratio of useful energy or other useful physical outputs obtained from a system, conversion process, transmission or storage activity to the input of energy (measured as kWh/kWh, tonnes/ kWh or any other physical measure of useful output like tonne-km transported, etc.). [IPCC SRREN, 2011, Glossary]*

POWER CONSUMPTION ON STANDBY AND SLEEP MODE

A lot of energy is used to power devices that are switched on, but are not in use at the moment. They are in STANDBY or SLEEP MODE. According to a study conducted by the Fraunhofer Institute for Systems and Innovation Research in Germany, ELECTRICAL EQUIPMENT ON STANDBY CONSUMES AS MUCH ELECTRICITY IN TOTAL AS THAT PRODUCED BY ALL THE EXISTING WIND ENERGY PLANTS. AROUND NINE BILLION KILOWATT-HOURS ARE WASTED EVERY YEAR IN THIS INCREDIBLE WAY. To run a microwave oven digital display, 5W of power is required. Over the useful life of the oven, the energy cumulated in this way can exceed the amount of electricity used by the appliance for cooking! [Bârsan, 2007].

The analysis conducted at the FACULTY OF MECHANICAL ENGINEERING IN BELGRADE practically confirmed the above results. The power consumption of the personal computer in SLEEP MODE was 2 Wh, while in STANDBY (IDLE) mode it was as much as 92 Wh [Đorđević, 2012]. The Japanese company "EIZO-NANAO", defined reducing the energy consumption in STAND-BY mode to less than 1 Wh [Bârsan, 2007] as the main goal of the research.

18. Figure_The display of the microwave oven consumes 5 W of electricity when switched on

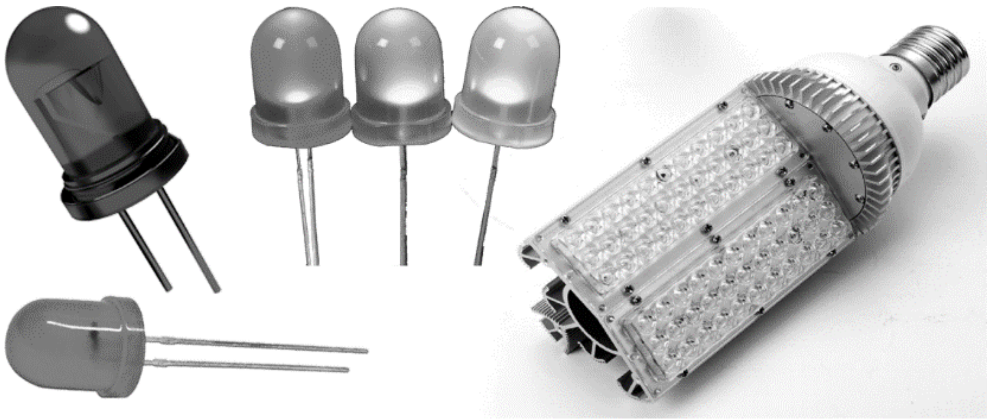
In addition to standby and sleep mode, most devices consume electricity even when switched off (so-called "VAMPIRE" consumption). In order to reduce this consumption, it is not only sufficient to switch off the devices, but also to disconnect them from the sockets. In Denmark, "vampire" consumption accounts for 10% of total energy consumption, and in Germany, every household loses, on average, about 45 W, which emits 14 million tonnes of CO_2 into the atmosphere [Reader's Digest, Serbia, July 2009].

REDUCTION OF ENERGY CONSUMPTION

LED VS. INCANDESCENT LIGHT BULB

LEDs (Light Emitting Diode) have a lot of advantages over conventional bulbs:

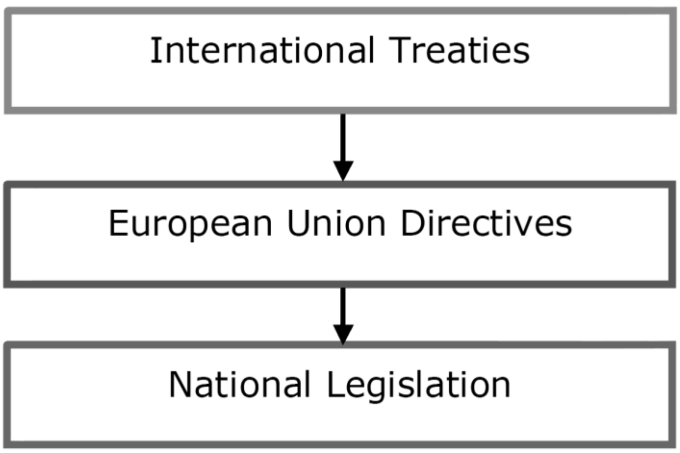
_they don't have a heating wire filament that will burn out, so they last longer,
_their little plastic bulb makes them more durable,
_they are easier to mount in modern electronic devices,
_their main advantage is efficiency.



19. Figure_LED and LED-based light bulb (Moon Raker 30W LED Light)

Incandescent light bulbs generate a lot of heat due to wire filament heating. It's completely wasted energy because a huge amount of energy is consumed as heat, not to get light. LED generates very little heat. Much of the electricity goes directly to light generation, which significantly reduces the demands for electricity.

DESIGN FOR COMPLIANCE WITH REGULATIONS AND STANDARDS



20. Figure: Legislation levels in the EU

EU REGULATION

At EU level, the ECODESIGN-related normative framework can be found in a wide range of environmental protection areas, such as:

_SWM – Solid Waste Management,
_EuP – Energy using Products, and now ErP – Energy related Products
_industrial machines,
_Restrictions on the use of certain Hazardous Substances (RoHS),
_telecommunications and radio equipment,
_liability for damaged parts of the product,
_product safety...

STANDARDIZATION ORGANIZATIONS - INTERNATIONAL

International standards are prepared by:

_ISO - The International Standardization Organization (founded in 1947),
_IEC - The International Electro-technical Commission (founded in 1906),
_ITU - The International Telecommunications Union (founded in 1865).

STANDARDIZATION ORGANIZATIONS - REGIONAL

Regional standards are prepared by specially established bodies such as:

for Europe:
CEN – The European Committee for Standardization,
CENELEC (ESCE) – The European Standardization Committee in Electrotechnics,
ETSI (EIETS) – The European Institute for Electro-Technical Standardization,

for America:
COPANT – The Pan-American Standardization Commission
MERCOSUR – The South Common Market

STANDARDIZATION ORGANIZATIONS - NATIONAL

Each country has a national standardization system and organizations for the adoption of standards:

_AUSTRIA: Austrian Standards Institute – ON,
_UNITED KINGDOM: British Standard Institution – BSI,
_GREECE: Hellenic Organization for Standardization – ELOT,
_ROMANIA: Romanian Standard Institution – ASRO,
_SERBIA: Institute for Standardization – former JUS, now SRPS...

ISO 14000 SERIES STANDARDS

In the field of environmental management, the most relevant series of international standards is ISO 14000. The ISO 14000 standard family consists of a set of standards covering six areas:

_Environmental Management System,
_Environmental Audit,
_Environmental Evaluation of Performance,
_Environmental Labelling,
_Evaluation of the Life Cycle of Products,
_Evaluation of the Environmental Aspects in Production Standards.

SYSTEM AND PRODUCT ORIENTED STANDARDS WITHIN THE ISO 14000 FAMILY OF STANDARDS

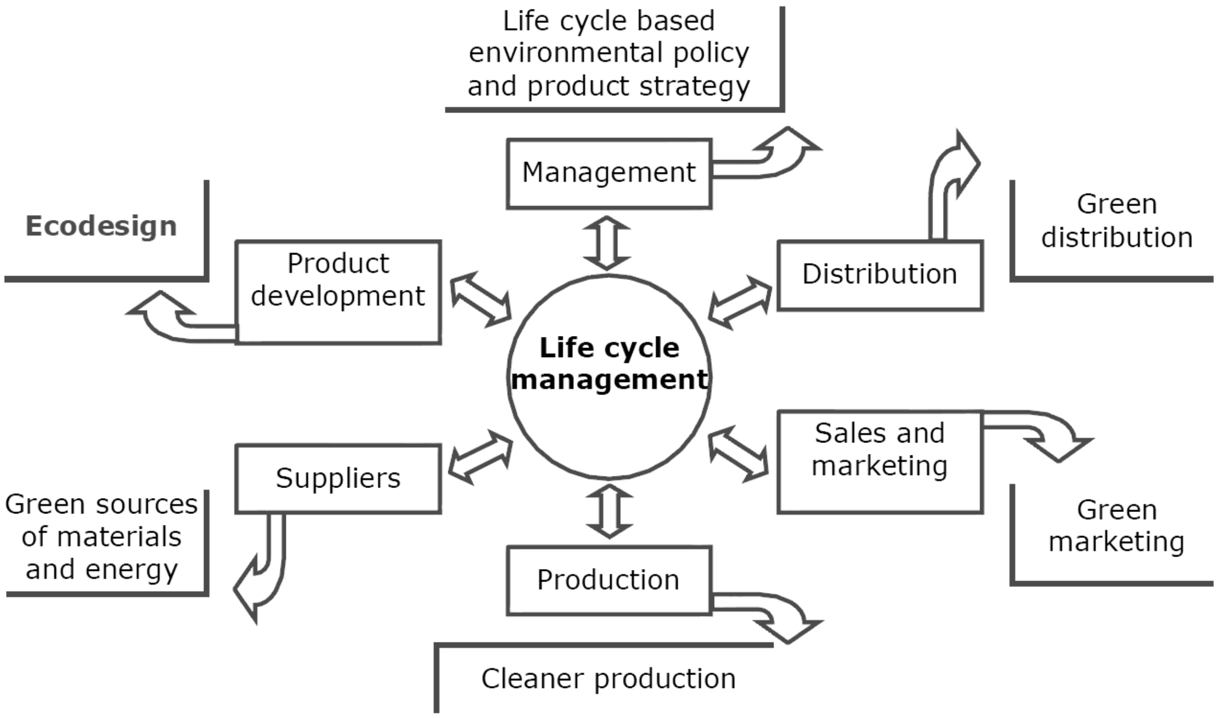
System-oriented standards:

_ISO 14001: 1996/2004 and 14004: 1997/2004 – Environmental Management System,
_ISO 14010: 1998, 14011: 1998, 14012: 1998 and 14015: 2001 - Environmental Auditing,
_ISO/TR 14061: 1998 – Informative Reference Material to Assist Forestry Organizations in the Use of ISO 14001 and ISO 14004,
_ISO 14031: 1999, TR 14032: 1999 – Environmental Performance Evaluation,
_ISO 9000: 2000 – Quality Management Systems,
_ISO 19011: 2002 – Guidelines for Quality and/or Environmental Management Systems Auditing.

Product-oriented standards:

_ISO 14020: 1998, 14021: 1999, 14024: 1999, and TR 14025: 2000/2005 – Environmental Labelling,
_ISO 14040: 1997/2005, 14041: 1999, 14042: 2000, 14043: 2000, 14044: 2005, TR 14049: 2000, TR 14048, TP 14047 – Life Cycle Assessment,
_ISO GUIDE 64: 1997 - Guide for Inclusion of Environmental Aspects in Product Standards,
_ISO TR 14062: 2002 – Integrating Environmental Aspects Into Product Design and Development,
_ISO DIS 14063 – Environmental Communication,
_ISO DIS 14064 – Greenhouse Gases.

PRODUCT LIFE CYCLE MANAGEMENT



21. Figure_Product life cycle management [Source: Bârsan, 2007]

ECO-MANAGEMENT AND AUDIT SCHEME - EMAS

EMAS (Eco Management and Audit Scheme) is a program under which companies within the EU operate and which, in addition to other systems and regulations, provides the basic parameters as guidance for the product development team. It was established by EU REGULATION 1836/93, WHICH WAS LATER REPLACED BY EU COUNCIL REGULATION 761/01. It includes corporate objectives for the design process, for the company and for designers. The board of directors of the company should explain to the designers the necessity of considering environmental issues. It deals with:

_new laws and regulations related to environmental issues,
_the strategy of the company which is seeking for new markets,
_new technologies in product manufacturing or packaging,
_changes in the customers' consciousness, expectations and lifestyle.

22 Figure_EMAS

Approaches used to measure environmental performance:

_input measures focusing on the effectiveness of environment-related business processes within the company,
_emissions/waste measures tracking the mass or volumes of emissions to air, soil, water and solid waste disposal,
_resource measures recording the consumption of resources,
_efficiency measures monitoring wastage in the use of energy and materials,
_customer measures concerned with the satisfaction and behaviour of customers,
_financial measures assessing the costs and benefits of environment related actions,
_risk measures assessing the likelihood and the consequences of environmentally harmful events.

LIFE CYCLE ASSESSMENT - LCA

LIFE CYCLE ASSESSMENT - CORE OF ECODESIGN

In order for ECODESIGN to be implemented in the product design phase, those working on product development and design need to know how impacts on the human environment arise, how they can be calculated, how they can be presented and finally, how they can be reduced. Therefore, a basic understanding of product Life Cycle Assessment – LCA is necessary.

BASICS OF LIFECYCLE ASSESSMENT (LCA)

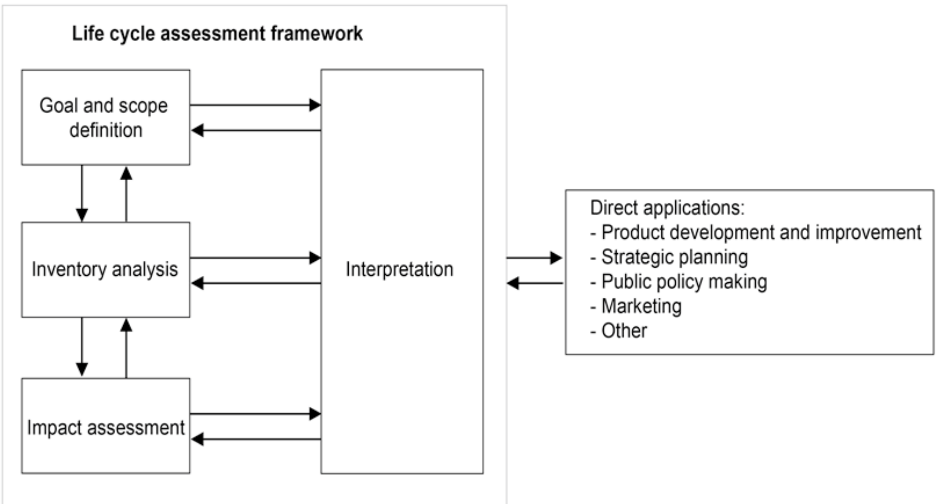
The LCA study has been standardized as an international standard from the ISO 14040 (1997) series of standards.

The LCA is a methodology for assessing environmental impacts associated with all the stages of the life cycle of a commercial product, process, or service.

By quantifying consumption and pollution emissions, the environmental impacts can be assessed and calculated. All environmental effects are considered to be IMPACTS, i.e. ENVIRONMENTAL IMPACTS. They occur due to the consumption of natural resources and due to the release of pollutants into the environment. Since different types of resources are used, also different environmental impacts occur.

According to ISO 14040 from 2006, the LCA study is divided into four phases, as follows:

_goal & scope definition,
_Life Cycle Inventory (LCI) analysis,
_Life Cycle Impact Assessment (LCIA),
_life cycle interpretation.



23. Figure_ LCA phases, as described by ISO 14040

A / LIFE CYCLE: Successive (consecutive, repetitive) and interconnected stages of the product system, from the collection (acquisition) of raw material from natural resources to final disposal.

B / LIFE CYCLE ASSESSMENT: Collection and assessment of inputs and possible impacts on the environment of the product system during its life cycle. LCA IS AN ITERATIVE PROCESS. Life cycle analysis is more or less A COMPROMISE BETWEEN COMPLEXITY AND PRACTICALITY, and LCA is the best established methodology for systematic analysis of environmental impacts of each of the product's (or service's) life cycle phases [Vujičić, 2010].

The LCA is a quantified CRADLE-TO-GRAVE or CRADLE-TO-CRADLE environmental audit. ANALOGY IS MADE WITH COOKING: it is not only important to cook lunch, but also to obtain ingredients, bring them to the kitchen, look at the recipe, cook and finally take care of the leftovers. It is a relatively new area. The first instructions were given by SETAC (Society of Environmental Toxicology and Chemistry) in 1993. The first ISO standard was issued in 1997, and new series of standards are now being issued. In the revision of the standard in 2006, there were no substantial changes in the LCA method.

LCA VARIANTS (PARTIAL ANALYSES) – OPTIONS FOR DETERMINING BOUNDARIES OF THE SYSTEM

CRADLE-TO-GRAVE

CRADLE-TO-GRAVE is an analysis of the entire life cycle of a product from RAW MATERIALS – "CRADLE", through manufacture and use to THE END OF LIFE CYCLE (DISPOSAL PHASE) – "GRAVE". For example, paper is made from wood, and can be recycled to cellulose insulation (fibrous paper), and then used to save energy by insulating ceilings for 40 years, while saving 2,000 times more energy from fossil fuels used in its production. After 40 years, the cellulose fibers change and the old fibers are disposed of, probably incinerated. All inputs and outputs have been considered for each of the product life cycle phases.

CRADLE-TO-CRADLE

CRADLE-TO-CRADLE is a special type of CRADLE-TO-GRAVE analysis, where AT THE END OF THE PRODUCT LIFE CYCLE IS THE RECYCLING PROCESS. There are CLOSED LOOP RECYCLING – identical products (e.g. glass bottle is recycled into a glass bottle), and OPEN LOOP RECYCLING – different products (e.g. obtaining glass wool from recycled glass bottles).

CRADLE-TO-GATE

CRADLE-TO-GATE IS A PARTIAL ANALYSIS OF THE PRODUCT LIFE CYCLE FROM RAW MATERIALS ("CRADLE") TO THE "GATE" OF THE FACTORY. The use and disposal phase of the product is usually omitted. It is used to determine the environmental impact of manufacture. CRADLE-TO-GATE analyses are sometimes the basis for Environmental Product Declarations - EPD.

GATE-TO-GRAVE

GATE-TO-GRAVE involves processes from the moment of use of the product to the end of its life cycle (all POST-PRODUCTION PROCESSES). It is used to determine the impact of the product from the moment of leaving the factory.

GATE-TO-GATE

GATE-TO-GATE is a partial LCA study based only on “ONE VALUE-ADDED PROCESS” throughout the entire production chain. It contains processes exclusively during the production phase. It is used to determine the environmental impact of a single production step or process.

LIST OF ISO STANDARDS RELATING TO LCA

NEW VERSIONS:

ISO 14040: 2006:	LCA principles and framework,
ISO 14044: 2006:	LCA requirements and guidelines,
ISO 14047: 2003:	examples of application of 14042,
ISO 14048: 2002:	LCA data documentation format,
ISO 14049: 2000:	examples of application of 14041 to goal and scope definition and inventory analysis,
ISO 14062: 2002:	integrating environmental aspects into product design and development.

OLD VERSIONS:

ISO 14040: 1997:	LCA principles and framework,
ISO 14041: 1998:	LCA goal and scope definition and inventory analysis,
ISO 14042: 2000:	LCA life cycle impact assessment,
ISO 14043: 2000:	LCA life cycle interpretation.

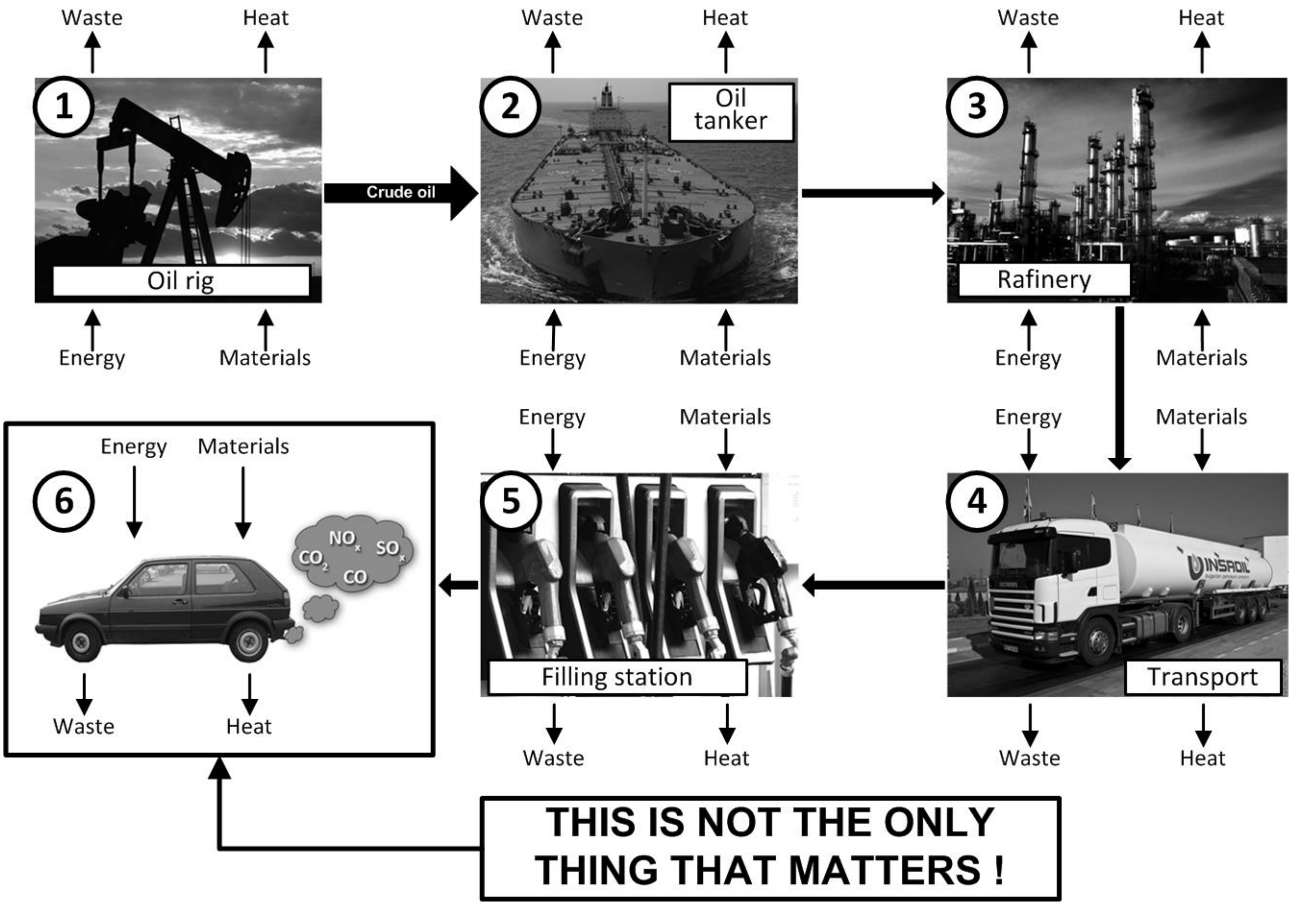
WHY IS LCA THE MOST COMPREHENSIVE TOOL?

“PROBLEM SHIFTING” FROM ONE PHASE TO ANOTHER IS NOT POSSIBLE, as LCA takes into account all phases of the life cycle. For example, replacing the car's steel frame with aluminum one can make it lighter and lower the fuel consumption, but more energy is consumed for aluminum production, and these factors are appropriately assessed one over the other during the LCA. In addition, LCA COVERS A WIDE RANGE OF ENVIRONMENTAL IMPACTS, not just e.g. carbon dioxide and energy.

The complexity of the problems solved by the LCA study can best be seen in the example of a car, asking the question:

What is the environmental impact of burning 1 litre of fossil fuel in a car?

The answer to this question is not simple, because it is not just the emitted gases, but the entire HIDDEN HISTORY!



24. Figure_Hidden history of 1 litre of fossil fuel

ADVANTAGES AND DISADVANTAGES OF LCA

The main advantages of the LCA study are as follows:

_it gives an overview of complete systems,
_identifies critical parts of the production and use,
_identifies knowledge gaps,
_gives guidelines for actions,
_increases awareness of environmental issues,
_changes the discussion from single issues to global and comprehensive thinking,
_provides a basis of information in the environmental debate.

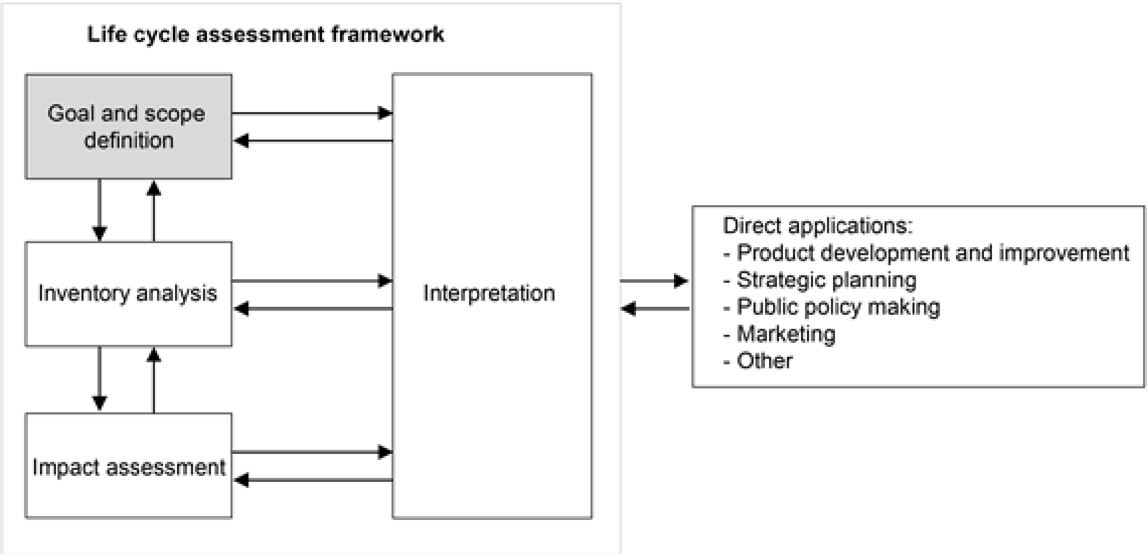
[Joenson, 1996]

On the other hand, the LIMITATIONS of the LCA study are as follows:

_the quality of the LCA depends on the available data, boundaries set, allocation rules adopted, assumptions made, the relevance of functional unit,
_the results may be difficult to evaluate,
_knowledge of complex processes is limited,
_until now, assessments have been directed towards potential, and not actual, effects,
_the evaluations are based on both scientific data and various subjective evaluations of different kinds,
_LCA requires a great deal of work, and therefore time, which makes it expensive

[Joenson, 1996]

GOAL AND SCOPE DEFINITION



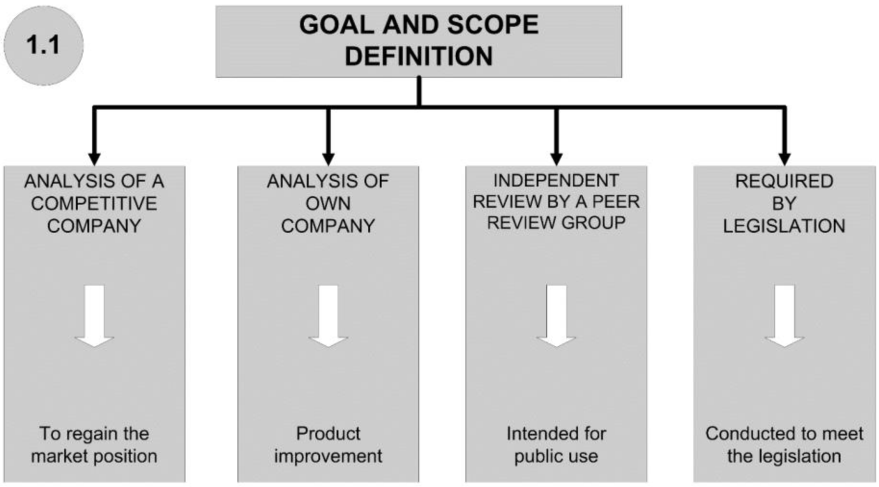
25. Figure_LCA goal and scope definition – diagram according to ISO 14040: 2006

At this stage, a work plan is prepared for the entire LCA study. According to ISO 14041 (1998E) this stage of LCA is divided into the following steps or elements:

_goal of the study,
_scope of the study,
_function, functional unit and reference flow,
_initial system boundaries,
_description of data categories,
_criteria for initial inclusion of inputs and outputs,
_data quality requirements,
_critical review,
_study report.

TARGET AUDIENCE

By defining the goal, the questions why to perform the LCA study, which is the target audience and in which areas it is applicable, are answered. The target audience can be customers or stakeholders. The results, presented by the LCA study, can also be used for internal purposes within companies.



26. Figure_Block diagram of the goal and scope of the LCA

SCOPE DEFINITION

The SCOPE DEFINITION includes the definitions of the function of the product and its parts, the functional unit and the reference flow, the concept of the product system, alternative product systems and setting the system baselines and data quality requirements.

Suggestions by ISO 14040 and 14041 regarding the LCA scope definition differ slightly. Under the heading “scope of the study” in ISO 14040 (1997E), clause 5.1.2 (referring to ISO 14041, clause 5.3.1), a list of elements to be considered and clearly described is given:

_the function of the system,
_the functional unit,
_the system to be studied,
_system boundaries,
_allocation procedures,
_the types of impact and methodology of impact assessment and subsequent interpretation to be used,
_data requirements,
_assumptions,
_limitations,
_initial data quality requirements,
_the type of critical review, if any, and
_the type and format of the report for the LCA study.

FUNCTION AND FUNCTIONAL UNIT

THE FUNCTION OF THE PRODUCT is what the product provides to the user. The function IS AN ABSTRACT TERM and may depend on the user's point of view and expectations.

THE FUNCTIONAL UNIT quantifies the functionality of the product and makes it possible to measure this abstract quantity. In other words, the functional unit TRANSLATES THE ABSTRACT FUNCTION INTO A TECHNICAL, measurable unit.

At first glance, DEFINING THE PRODUCT FUNCTION is not such a difficult task. Let's imagine some products in the field of information technology and communications, for example different models of mobile phones. You could say that the function of a mobile phone is to give us the ability to make phone calls to other people. This is certainly true, but if you compare some of the mobile phones available on the market, some of them have a video camera, some allow access to the Internet, or the ability to listen to music, or contain an electronic personal organizer. The question to ask is:

Is the product a telephone that contains an electronic organiser, or is it an electronic pocket organiser with a telephone function; WHAT IS THE BASIC FUNCTION?

Before defining a functional unit, the corresponding basic function of the product must be known. In the case of multifunctional products, such as mobile phones, the complexity of determining the appropriate basic function is obvious.

But what about the other products, which seem to have only one function? What if the use of a product (e.g. a car) was considered a symbol of social status?

EXAMPLE: OFFICE CHAIR

WHAT IS THE FUNCTION OF THE OFFICE CHAIR?

The most general definition of its function would be “providing a place to sit in the office”.

And what if the term “comfortable seating” is included in the definition?

To ensure a comfortable seating, the office chair must have some additional features and functions. They include, amongst others:

_seat height adjustment,
_adjustable backrest,
_adjustable armrests,
_shock absorber for sudden sitting down.

The example shows that in order to meet the new function definition, it is necessary to provide additional parts and components.

Now, WHEN THE OFFICE CHAIR FUNCTION IS KNOWN, THE FUNCTIONAL UNIT CAN BE DEFINED AS FOLLOWS:

“Provide a comfortable office chair, for an average person weighing between 50 and 120 kg, for 8 hours a day, five days a week for a period of 15 years” [Steelcase, 2003].

As can be seen from the previous definition, the functional unit contains a quantitative determination of the service life of the product.

27. Figure_Conventional office chair (left) and improved design (right) [Source: Wimmer, 2007]

EXAMPLE: HAND DRYER VS PAPER TOWELS

28. Figure_Paper towels vs electric hand dryer

WHAT WOULD THE FUNCTIONAL UNIT FOR THE HAND DRYER/PAPER TOWEL BE LIKE??

Defining a functional unit is crucial for comparative studies. If two products are to be compared, the functional unit must be the same. Also, alternative systems are defined with respect to the functional unit.

FUNCTIONS:	hand drying, elimination of bacteria
SELECTED FUNCTION:	hand drying (hygiene function is omitted, it would be part of a separate LCA study)
FUNCTIONAL UNIT:	1,000 pairs of dried hands
PRODUCT PERFORMANCE:	1 paper towel per hand,
REFERENCE FLOW:	2,000 paper towels,
COMPLICATIONS:	The technical specifications of the paper/dryer are/are not under the control of the user, i.e. a lot of people may take more than 1 towel and will not keep their hands under the dryer during the full time specified by the timer. But this should not be taken into account in this LCA study: it is more a product redesign problem.

REFERENCE FLOW

THE REFERENCE FLOW indicates the amount of product required to fulfill the function. The reference flow can be defined FOR THE ASSEMBLED PRODUCT and its entire function OR FOR ITS PARTS and components that perform the sub-function.

In the case of AN OFFICE CHAIR, the general function, i.e. comfortable sitting, can be achieved by using one part of the chair weighing approximately 20 kg. In order for the chair to fulfill the function of “adjustable armrests”, two armrests weighing 1.5 kg each are required.

PRODUCT SYSTEM

Another important step in determining the scope definition is to establish the concept of “PRODUCT SYSTEM”. THE PRODUCT SYSTEM IS NOT THE SAME AS THE PRODUCT! The term “PRODUCT” usually describes a fully assembled ready-to-use product. In the LCA study, and further in ECODESIGN, THE PRODUCT IS ONLY A PART OF THE PRODUCT SYSTEM. The assembled product can contain many parts and components, and the manufacture of each of them requires raw materials and production technology.

Taking into account all processes, as well as all inputs and outputs from these processes at all stages of the life cycle, A PRODUCT SYSTEM is realized.

A UNIT PROCESS is the smallest quantity or unit that a process can have (e.g. 2 kg of certain material, 5 MJ of energy required for production processes).

SYSTEM BOUNDARIES

When a product system is defined and unit processes as well as product-related activities are known, system boundaries can be defined, which should be consistent with the goal of the study. System boundaries are necessary to determine which unit processes and what activities in the product system should be considered in further calculations.

The goal and scope definition of the LCA study can VARY a lot FROM PRODUCT TO PRODUCT, EVEN FOR THE SAME PRODUCT in case the LCA study is carried out by different companies. These differences occur due to differences in parameter selection, data quality, different evaluation methods and databases, variation of system boundaries, etc.

Although the system boundaries vary, according to ISO 14041 (1998) there are several life cycle stages, unit processes and flows that should be considered as an example:

_inputs and outputs to the main production/process sequences,
_distribution/transport,
_production and use of fuel, electricity and heat,
_production of auxiliary materials,
_production, maintenance and DECOMMISSIONING[3] OF CAPITAL EQUIPMENT,
_supplementary operations, such as lighting and heating (OVERHEAD ENERGY[4]),
_other considerations related to impact assessment.

CAPITAL EQUIPMENT is equipment used in the production of products, provision of services, or sale, storage and delivery of goods. This equipment has a long lifespan so it is properly considered a fixed asset.

DEFINING SYSTEM BOUNDARIES

HOW SHOULD THE SYSTEM BOUNDARIES BE SET??

This question should be answered depending on:

_the goal and target audience,
_should all components or only the main ones be considered?
_should all stages of the life cycle be considered and how detailed?
_impact on global results, which is why the iterativity of LCA is important.

[3] *Formal process of removing something from active status,*
[4] *Overhead energy is defined in book Fundamentals Ecodesign on page 48.*

It is important to note here that according to ISO 14041 in the first phase of the LCA study (goal & scope definition), the STARTING (INITIAL) SYSTEM BOUNDARIES are set on the basis of "CUT-OFF"[5] rule and temporal, geographical and technology coverage, i.e. system boundaries.

TEMPORAL COVERAGE - the limit of transience or temporality, defines the time period for which the selected data are relevant.

GEOGRAPHICAL COVERAGE - determine the region where most of the required material is produced and where the product is used and disposed of.

TECHNOLOGY COVERAGE - defined by choice of technologies used in the product life cycle phases.

Chosen technologies can be old or new, current technologies. If appropriate data is available, it is possible to choose the technology and create a scenario that will be feasible in the future.

"CUT-OFF" RULE

The product system can contain many different processes and activities. Some of these processes have a significant impact on the LCA and on the environment, while others are negligible. From an economic and practical point of view, IT IS VERY IMPORTANT THAT THE PRODUCT SYSTEM CONTAINS ONLY SIGNIFICANT PROCESSES AND ACTIVITIES, because otherwise the LCA becomes a complex, time-consuming and expensive study. A decision based on MASS or ENERGY CONTENT is often used when defining a product system. In the case of a mass content criterion, if in a unit process the mass content is less than a certain quantity or percentage, then this unit process can be neglected. Said percentage may be freely chosen or determined. For example, it can be defined that if the mass content of a unit process is less than 5%, then we can ignore that process. The same can be done if the decision is made in relation to the energy content.

However, if the unit process contains TOXIC SUBSTANCES or PROBLEMATIC MATERIALS, such as chromium, this unit process, even in small quantities, can significantly contribute to environmental impacts. In this case, the unit process must be taken into account. Instead of defining a minimum mass content, which must be considered in the LCA study, we can also define a MAXIMUM MASS CONTENT. We call this case THE "CUT-OFF" RULE. Defining a "CUT-OFF" rule of 90% means that 90% of the mass content of all unit processes in the product system enters the LCA study, while the other 10% is negligible. In order to define the rules for decision-making, some experience is needed to avoid neglecting significant unit processes.

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[5] *According to [VROM & CML, 2001] defining the boundaries between the system and the environment, the "cut-off" criteria and allocation fall under the definition of the "Economy-environment" system boundaries in the 2nd phase of the LCA.*

ALLOCATION

In many processes, MORE THAN ONE PRODUCT is produced. In these cases, all INPUTS AND OUTPUTS FROM THE PROCESS MUST BE allocated to the given products.

ALLOCATION is the distribution and relating of inputs and outputs from the process with adequate products and by-products.

At this stage of the LCA study, the allocation procedures to be applied in the LCA study are defined. Accordingly, the allocation can be performed according to the following rules:

_ALLOCATION BY MASS – inputs and outputs from the process are distributed to all products in proportion to their mass content,
_ALLOCATION BY HEATING VALUE – inputs and outputs from the process are distributed to all products in proportion to their heating value. This allocation method is very often used in fuel production,
_ALLOCATION BY MARKET VALUE – inputs and outputs from the process are distributed to all products in proportion to their market value,
_ALLOCATION BY OTHER RULES – other methods may include exergy, amount of matter, etc.

Since the choice of allocation method can have a significant impact on LCA results, ISO RECOMMENDS TO AVOID ALLOCATION WHENEVER POSSIBLE. If it is not possible to avoid an allocation, the allocation method must be described in detail, as well as the sensitivity analysis of the results in relation to the choice of the allocation method. Also, ISO recommends that it is better to use the allocation based on physical quantities, such as mass and heating value, than the allocation with non-physical relations with the product, such as market value. There are two ways to avoid allocation:

_substitution,
_expansion of the system.

DATA QUALITY REQUIREMENTS

Data quality requirements must be established at the beginning of the study and must be documented, in order to define the required data characteristics for the LCA study. Data quality has a significant impact on the results of the LCA study. Basically, data quality is a compromise between feasibility and completeness (comprehensiveness) and depends on the quality of documentation.

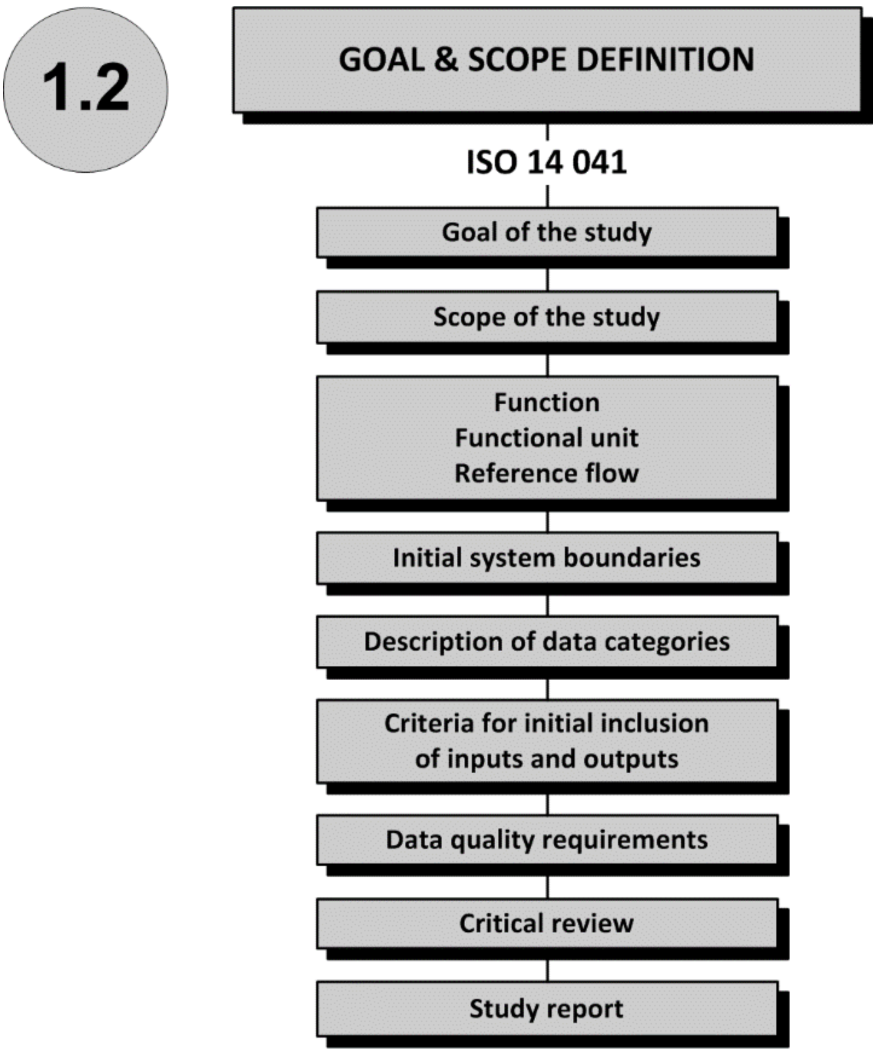
When considering data quality, the following items are taken into account:

_DATA ACQUISITION – are the data obtained by measurement, calculation or estimation? What are the shares of primary (in %) and secondary data (data from literature or databases),
_TIME-REFERENCE or TEMPORAL COVERAGE – when the data was collected and have there been any major changes since then that could affect the results?

_GEOGRAPHICAL REFERENCE or GEOGRAPHICAL COVERAGE – for which country or region are the data relevant?
_TECHNOLOGY REFERENCE or TECHNOLOGY COVERAGE – the best available technology. Are secondary data from literature or databases for modern (or obsolete) technology systems?
_PRECISION – do the data accurately represent the system?
_COMPLETENESS – are any data missing? How were the missing data collected?
_REPRESENTATIVITY, CONSISTENCY and REPRODUCIBILITY – are the data representative and can the same results be obtained again in the new analysis?

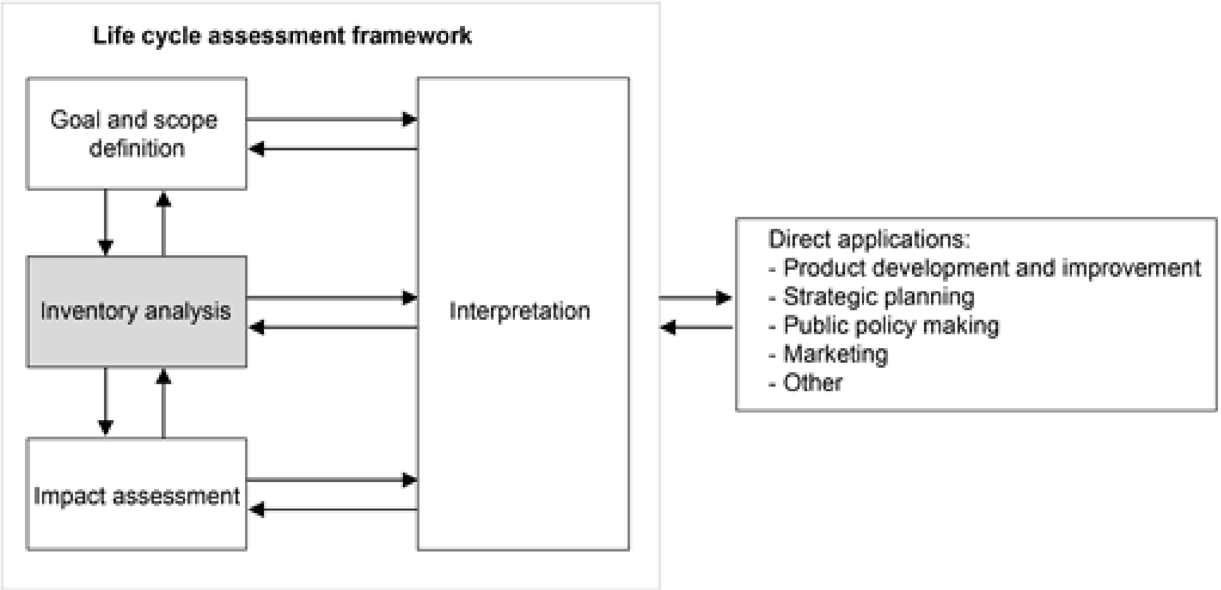
At this stage, it is still considered which data categories and which parameters are relevant and should be taken into account. For example, the “emissions to air” data category is rated as significant, and the corresponding parameters may be the generation of CO_2 or CH_4.

THE WRITING OF THE REPORT, which clearly shows the assumptions and decisions made during the goal and scope definition phase, is the last step in this phase of the LCA.



29. Figure_LCA goal and scope definition according to ISO 14041 (1998E)

LIFE CYCLE INVENTORY ANALYSIS – LCI



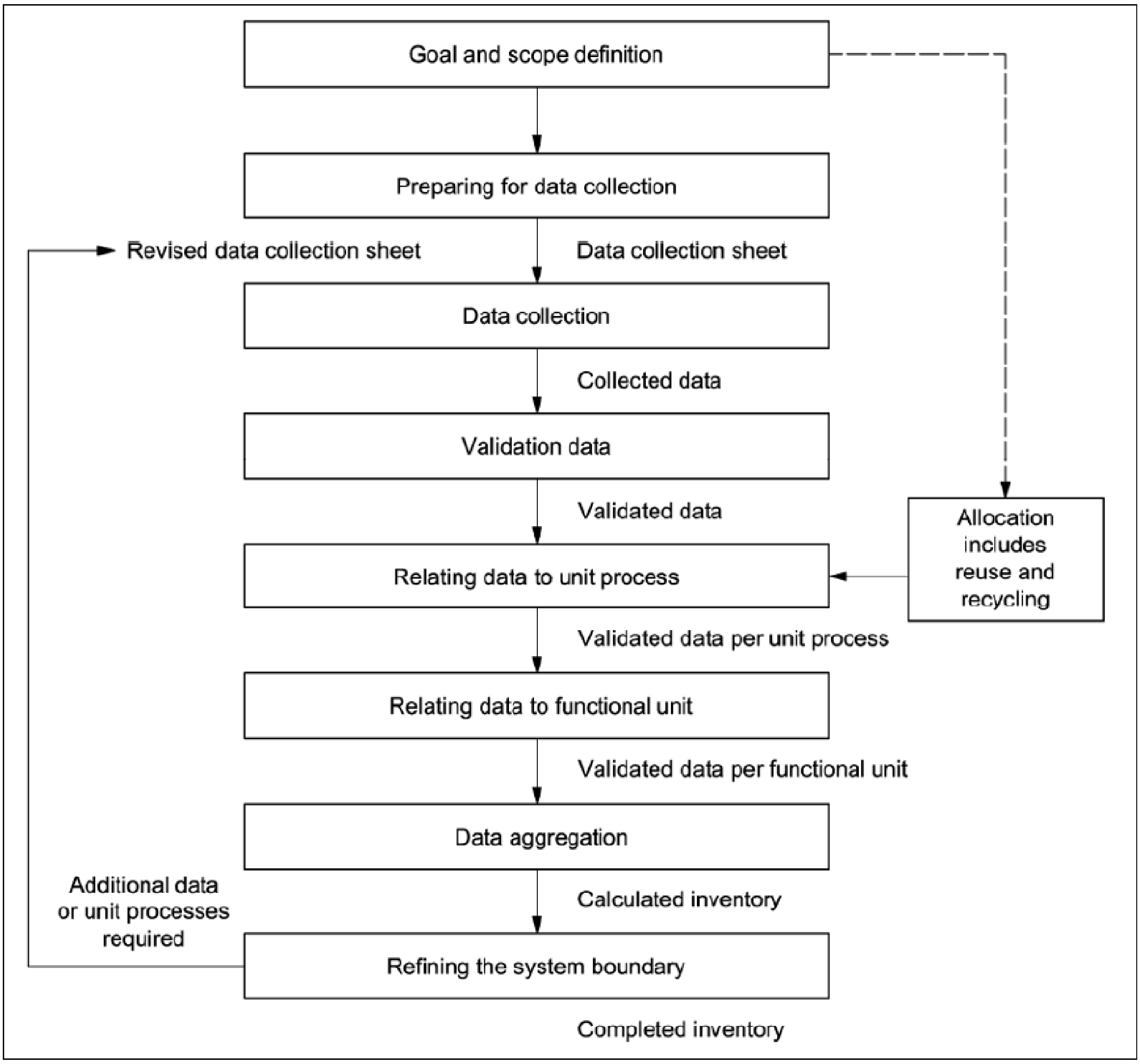
30. Figure_Life cycle inventory analysis – LCI – diagram according to ISO 14040: 2006

Inventory analysis is the stage in which the product system is defined. System boundaries are determined[6], flow diagrams with unit processes are drawn, data are collected for each process, allocations are made for multifunctional processes and final calculations are performed. The main result of this phase is a tabular overview of the inventory with quantified inputs and outputs in accordance with the functional unit.

ISO 14041 (1998E) divides the data collection procedure into the following steps:

_preparing for data collection,
_data collection,
_validation of data,
_relating data to unit processes,
_relating data to functional unit,
_data aggregation,
_allocation and recycling,
_refining the system boundaries, and additionally
_limitation of LCI, and
_LCI study report.

[6] *According to ISO 14041 (1998E), system boundaries are further discussed under the item "refining the system boundaries".*



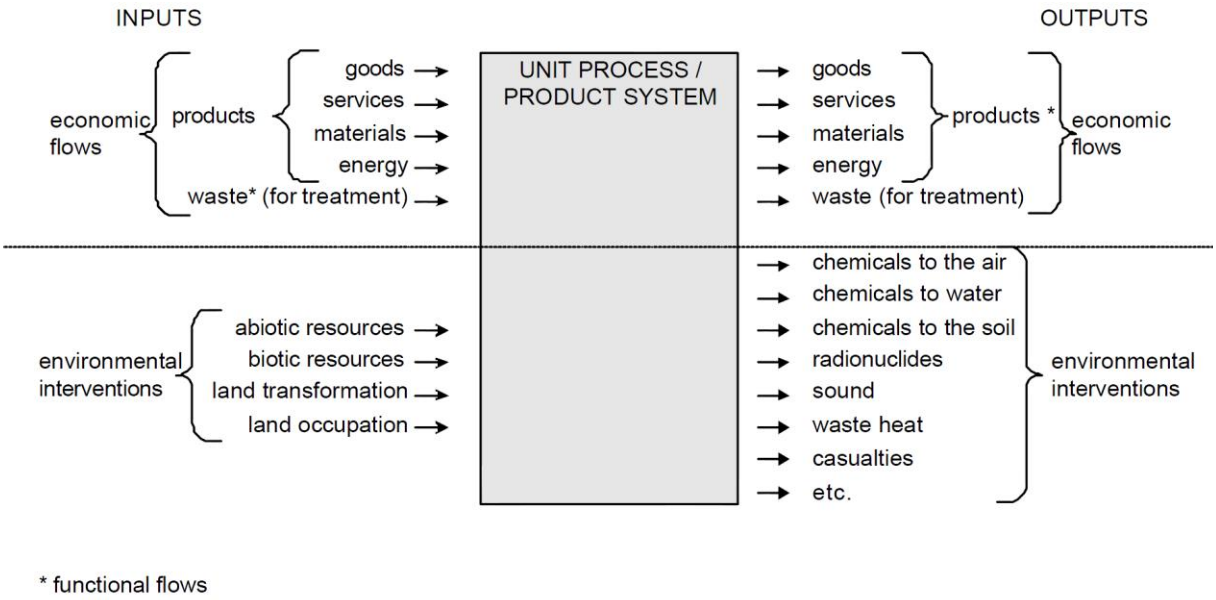
31. Figure_Data collection and calculation process [Source: GaBi Handbook PE International, 2010]

PREPARATION FOR DATA COLLECTION

In the first step, INPUT AND OUTPUT DATA FOR UNIT PROCESSES AND ACTIVITIES ARE COLLECTED. Each process has its INPUTS and its OUTPUTS. The INPUTS may be raw materials, and/or semi-finished products, and/or products, and/or energy. The OUTPUTS may be semi-finished products, and/or products, and/or emissions, and/or energy (heat...).

Drawing a PROCESS DIAGRAM helps to visualize the interconnection between processes.

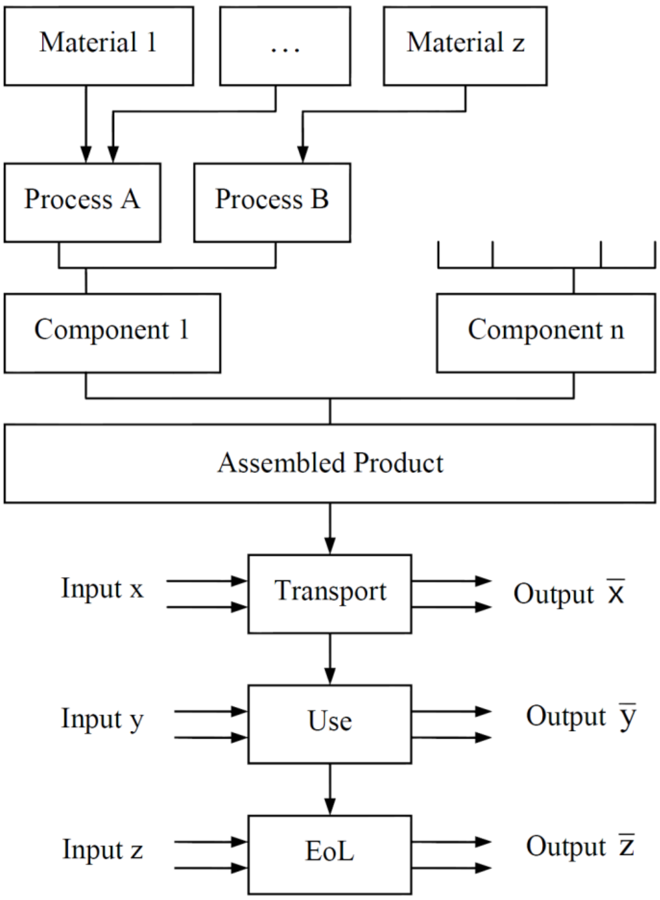
The interrelationship between products and activities in the product system is usually represented graphically by PROCESS DIAGRAM (PROCESS SCHEME), whereby a distinction should be made between the initial diagrams, at the level of all processes for each of the the life cycle phases, and detailed process diagrams, at the level of unit processes.



32. Figure_Environmental impacts and economic flows – inputs and outputs from the system [Source: VROM & CML, 2001]

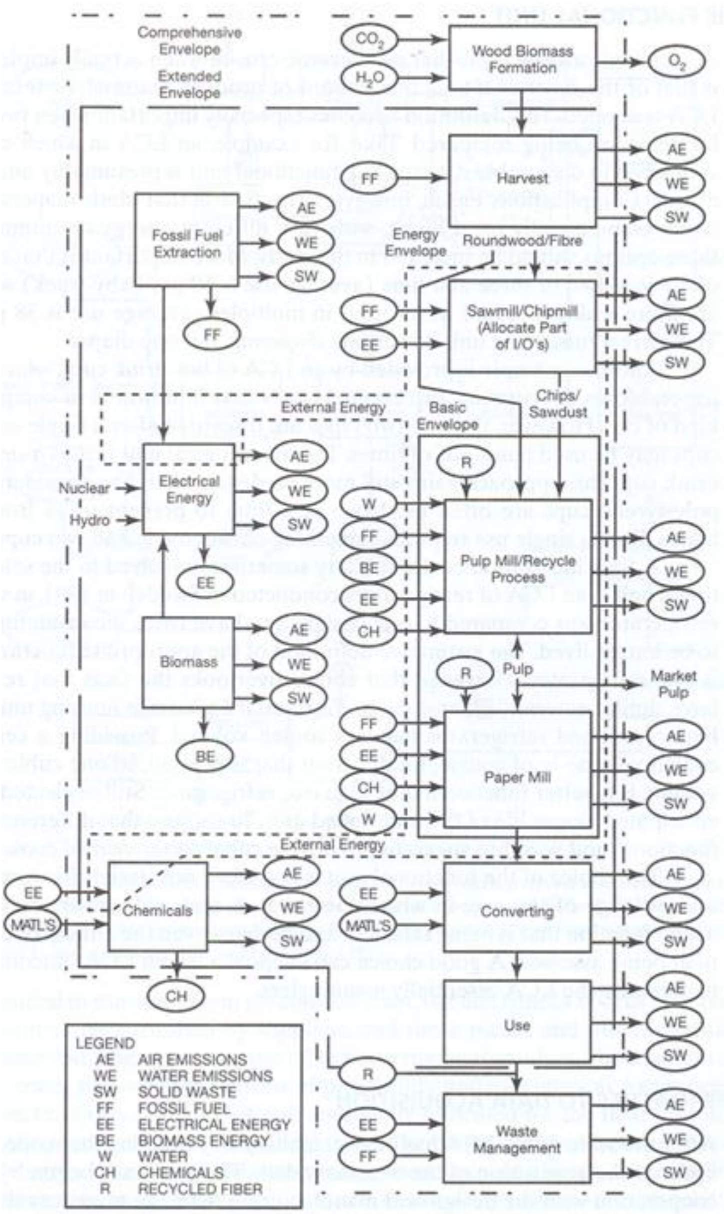
Each "branch" in the "process tree" represents a single activity or process, a so-called "UNIT PROCESS".

The arrows and lines show the respective INTERRELATIONSHIP of unit processes in the process scheme.



33. Figure_Process diagram of the product system [Source: Ostad, 2006]

For the product from Figure 33, (z) different materials were used to produce (n) different parts and components. All components are assembled into the final product. The process SCHEME SHOWS ALL SIGNIFICANT UNIT PROCESSES at different stages of the life cycle. Each of these life cycle phases has some input, e.g. energy, process or auxiliary materials, and creates some output, e.g. waste. These inputs and outputs are indicated by arrows. IN THE CASE OF RAW MATERIALS AND PROCESSES OVER RAW MATERIALS, INPUTS AND OUTPUTS ARE NOT DRAWN. This does not mean that these inputs and outputs do not exist, but that they have ALREADY BEEN CONSIDERED IN UNIT PROCESSES and therefore there is no need to redraw them. This means that care must be taken when drawing, interpreting and using such process schemes, in order to avoid losing input and output data or using them twice in further calculations. Therefore, A TRANSPARENT AND COMPREHENSIVE REPORT MUST BE PROVIDED.



34. Figure_Paper production flow diagram [Source: Morris, 2007]

DEFINING UNITS OF MEASUREMENT (e.g. meter, kilogram, joule…) as well as describing calculation and data collection techniques is also part of data collection.

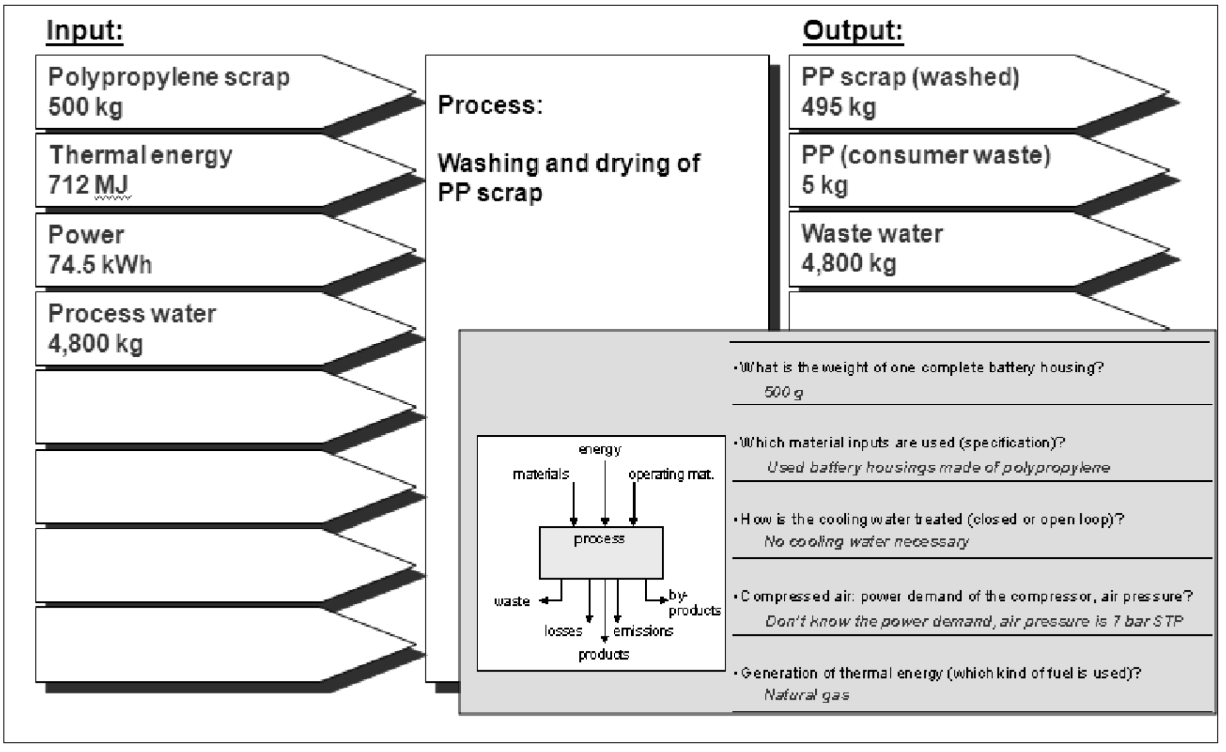
THE CALCULATION METHOD (CALCULATION TECHNIQUE) includes the quantification and interconnection of processes in accordance with the functional unit.

Different data collection techniques may be necessary for different parts and components in the product system. These techniques also depend on the qualifications and experience of the data collector. Therefore, clear documentation of WHICH TECHNIQUES AND PROCEDURES HAVE BEEN USED is necessary.

To obtain the data considered, we can use LCA SOFTWARE AND THEIR DATABASES, because there most of the data, for different stages of the life cycle, is stored. Missing data must be found IN THE LITERATURE AND PREPARED MANUALLY. Already evaluated products and scenarios, or comparisons with similar products, may be helpful in collecting new data.

DATA COLLECTION

If essential data is defined, the SECOND STEP, CALLED DATA COLLECTION, begins. Therefore, the INPUTS AND OUTPUTS OF EACH UNIT PROCESS MUST BE QUANTIFIED. This is the MOST TIME-CONSUMING part of the LCA study. The data collection period usually LASTS ONE YEAR (at least).



35. Figure_Example for data collection [Source: GaBi Handbook PE International, 2010]

In case of using different sources for data collection, these sources must also be documented. DATABASES with data on raw materials, production processes, transport, use and end-of-life data, help to collect the necessary data.

MISSING DATA MUST BE EITHER SPECIFICALLY MEASURED for a specific product, for example energy consumption during a specific production process, OR the required data may be COLLECTED USING PRODUCT LIFECYCLE SURVEYS.

The data for the USE PHASE depends not only on the performances of the product, but also on its WAY OF USE and USER BEHAVIOR when using the product. Differently modeled usage scenarios allow a gradual approximation of the required data.

Let's imagine a washing machine used in a private household and another one used under group housing conditions, such as a dorm. The private household washer is used several times a week, while the dorm washer is used several times a day. It is clear that the use scenario of these two machines is completely different. Energy consumption, water consumption and washing detergent consumption as well as the amount of waste water produced and heat emissions are also different. The approach to data collection is to consider the average amount of energy, water and detergent needed for washing, as well as the average number of uses.

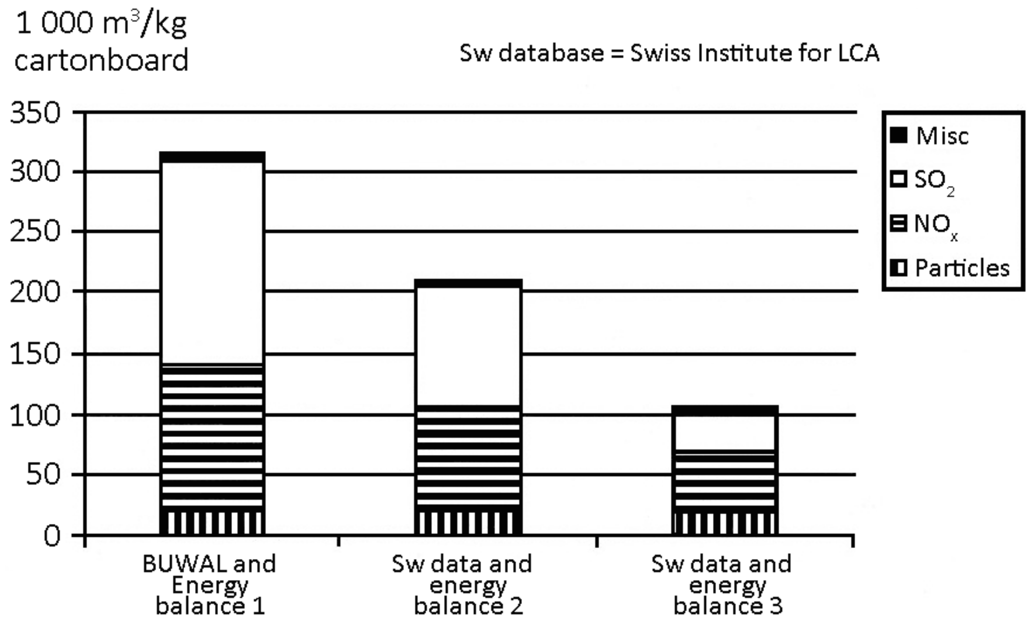
TRANSPORT data is usually known, as well as what type of transport is used and the distance travelled.

END-OF-LIFE data should include today's methods of disposal. Current waste disposal methods are considered as “worst-case” scenarios, so future technologies are expected to prove more efficient and with better results in waste disposal. Future technologies can only be considered if the product has a long lifespan. End-of-life data include, but are not limited to, disposal methods, such as, incineration, recycling or dumping to landfills, as well as the waste collection method.

Once the processes involved are understood, data collection should begin. THE BEST DATA ARE THOSE PROVIDED BY THE MANUFACTURER. However, data are often not readily available. Then you have to rely on DATABASES and LITERATURE. Databases and specialized software, e.g. GaBi or Sima Pro, are very important since they use a large number of databases from different institutions, e.g. SWISS INSTITUTE FOR LCA. Using the databases is invaluable, but they're kind of like a black box. Some of the databases are:

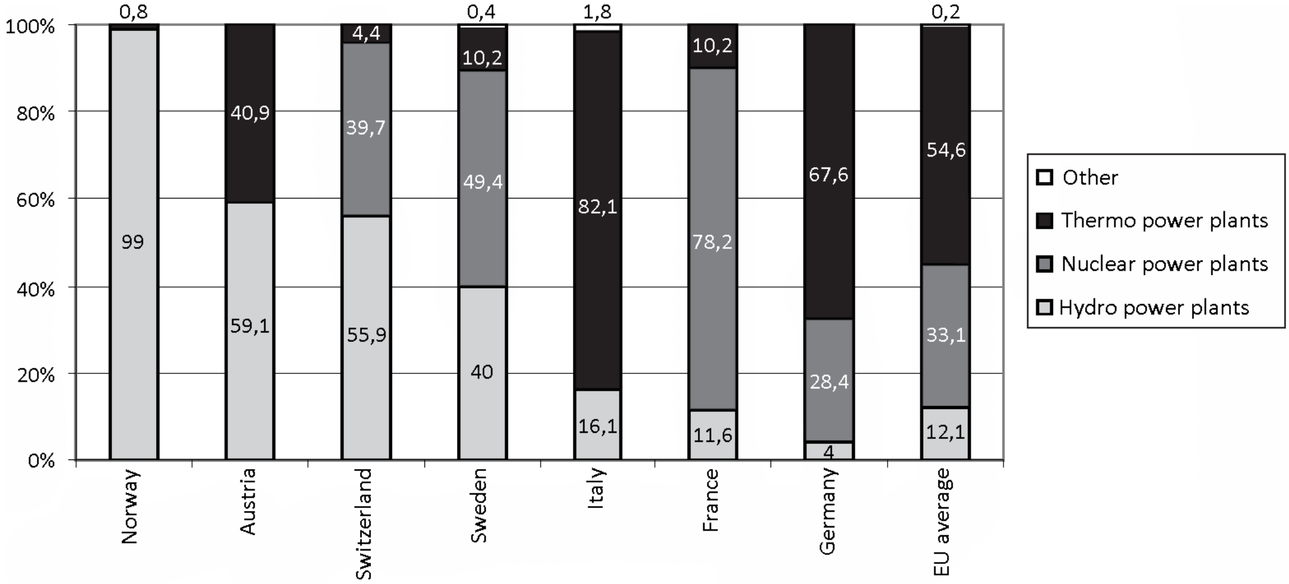
_BUWAL 250,
_ECOINVENT,
_ETH-ESU 96,
_IDEMAT 2001,
_FRANKLIN US LCI,
_IVAM 4.0,
_FEFCO...

Depending on the data/databases being applied, the results are likely to be different. Due to the use of data from different databases, differences in emissions may occur even for the same products, Figure 36.



36. Figure_Air emissions from the same cardboard boxes in relation to different databases [Source: Joenson, 1996]

WHY IS THERE SUCH A VARIATION IN THE DATA ???



37. Figure_ Electricity production in some of the EU countries [Source: Morris, 2007]

Data variation occurs for a number of reasons:

_entries in the databases were made by different institutions,
_databases vary in complexity and completeness,
_there are temporary and geographical specificities – e.g. aluminum produced in two different countries will result in different CO_2 emissions: e.g. Switzerland generates the majority of electricity from hydroelectric power plants, resulting in low CO_2 emissions, while e.g. Germany generates the bulk of its energy by fossil fuel thermal power plants, which means that CO_2 emissions are significantly higher than those in Switzerland...

VALIDATION OF DATA

After collecting the data, ISO 14041 (1998) proposes that the COLLECTED DATA BE VALIDATED FOR QUALITY. BALANCE OF MASS AND ENERGY around the unit process or comparison with emission factors generated when burning fossil fuels, help to verify the validity of the data. COMPARISON OF THE TOTAL INPUT AND OUTPUT FROM THE PRODUCT SYSTEM WITH THE SUM OF INPUTS AND OUTPUTS OF INDIVIDUAL UNIT PROCESSES IS ANOTHER APPROACH TO DATA VALIDATION (determining whether 100% of all processes within the system boundaries have been taken into account). If, in some way, it is not possible to collect data for a particular process, it must be documented how that process will be treated. If this process is not very important, then it can be neglected. If it is suspected that it is important, then validated data from a similar process are taken. It takes a lot of experience to make a move like this.

RELATING DATA TO UNIT PROCESSES

First, the REFERENCE FLOW MUST BE DEFINED FOR EACH UNIT PROCESS. The reference flow can be 1 kg for mass or 1 J for energy. Let's assume that a mass-related reference flow is selected. Then all the inputs and outputs are related to that reference flow. THIS MEANS THAT THE INPUT AND OUTPUT DATA OF THE UNIT PROCESSES ARE DIVIDED BY THE MAIN MASS OUTPUT OF THE CONSIDERED UNIT PROCESS. THE MAIN OUTPUT MAY BE A MATERIAL, COMPONENT OR THE ENTIRE, ASSEMBLED PRODUCT. The result of this division is called "ENVIRONMENTAL LOAD BY UNIT PROCESS". INPUT AND OUTPUT DATA ARE EXPRESSED PER WEIGHT UNIT OF THE MAIN PROCESS OUTPUT**.** For example, if the input to the welding process is a certain amount of energy and the main output is a certain number of kilograms of welded material, then the environmental load by this unit process is expressed in [J/kg] or [W/kg] .

RELATING DATA TO FUNCTIONAL UNITS

To relate the data to the functional units, WE MUST RELATE THE INPUTS AND OUTPUTS OF THE UNIT PROCESSES TO THE MAIN OUTPUT OF THE PRODUCT SYSTEM (not to the main output of the unit process). The result of this division is referred to as THE "ENVIRONMENTAL LOAD FROM THE PRODUCT SYSTEM".

The environmental load from the product system is calculated as follows:

_first, the partial contribution of single-member systems to the main output of the product system is calculated,

_then, it is MULTIPLIED BY THE ENVIRONMENTAL LOAD from each member of the system and

_summarized for all members of the system.

THE COMPONENT SYSTEM (SINGLE-MEMBER SYSTEM) is part of the product system concept, but not for the entire product, but only for one of its parts or components.

The result of the calculation of the total environmental load of the product system is referred to as the "INVENTORY OF THE PRODUCT SYSTEM RESULTS" or, in short, the "INVENTORY OF THE RESULTS".

It is also possible to calculate the environmental load from the product system for each phase of the life cycle. Advantageously, the phases that contribute most to the environmental load can be easily monitored.

DATA AGGREGATION

To simplify further calculations, input and output data can be AGGREGATED. This means that the parameters of the values, from the different processes, can be combined in case the processes are the same. Following the example on welding, this means that if the welding process is performed on different parts and components and if the materials to be welded are the same, the environmental load value of these processes can be aggregated. In other words, THE SAME INPUT AND OUTPUT DATA OF DIFFERENT UNIT PROCESSES ARE AGGREGATED IN A SINGLE PARAMETER. Another approach for aggregating data is MERGING TOGETHER THOSE DATA BELONGING TO THE SAME ENVIRONMENTAL IMPACT CATEGORY. For example, carbon dioxide (CO_2) and methane (CH_4) gases contribute to global warming, and can therefore be combined into one parameter. On the one hand, this has REDUCED THE AMOUNT OF DATA, but on the other hand, this has ALSO REDUCED THE TRANSPARENCY OF DATA.

The first calculated results are obtained by complementing the above steps. The LCA study should be understood as an ITERATIVE PROCESS. In the SENSITIVITY ANALYSIS, THE SIGNIFICANCE OF UNIT PROCESSES AS WELL AS THE SIGNIFICANCE OF INPUTS AND OUTPUTS CAN BE VERIFIED. In case of lack of significance, in accordance with the defined "CUT-OFF" decisions, certain unit processes and inputs and outputs may be excluded from the calculation. Sensitivity analysis can also lead to the inclusion of new unit processes and data that were assessed as significant during the analysis. It is clear that, by including and excluding data, the previous system boundaries will change. The new boundaries will produce new calculated results.

ALLOCATION AND RECYCLING

In the previous considerations, it was implicitly assumed that each unit process has only one input and output.

BUT HOW DO WE HANDLE THE DATA IF, IN A UNIT PROCESS, THERE IS MORE THAN ONE INPUT OR OUTPUT ?

In this case, in accordance with ISO 14041 (1998E), allocation mast be applied. During the allocation process, the inputs and outputs of the unit processes are divided by the main output of the unit process. To be able to perform an allocation, we need an allocation factor. The allocation factor can be based on physical quantities such as mass, energy or volume or on economic quantities such as the selling price.

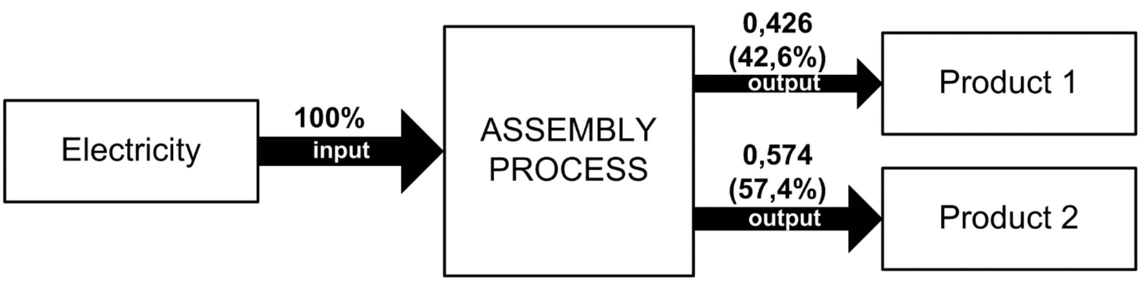
EXAMPLE 1:

Let's think about a company that produces two different products. Suppose that these production processes require a certain amount of electricity and assume that only the main electricity input is known. Let's assume, further, that we want to do an assessment for only one of the two products. What amount of electricity is needed to produce the product. We can answer this question by determining the allocation factor.

Table 13: Allocation factor based on the sales price of the product

Product	Monthly production	Selling price per piece [$]	Total selling price [$]	Allocation factor [%]
Product 1	6,000	10	60,000	42.6
Product 2	4,000	20	80,000	57.4
Total	10,000	30	140,000	100

Table 13 specifies the allocation factor based on the selling price of the product (economic value of two products). Table 13 shows that 6,000 pieces of Product 1 are produced each month and sold at a price of $10 each, giving a total sales price of $60,000 per month. This represents 42.6% of the company's total revenue. This means that out of the total input (consumption) of electricity, 42.6% can be allocated to Product 1 and 57.4% to Product 2.



38. Figure_Allocation of electricity according to the market value when assembling two different products

EXAMPLE 2:

The manufacturer assembles a kettle A and kettle B. The only energy input is electricity. The allocation factor can be determined on the basis of the market value. The total selling price (not unit price) for kettle A is €100,000 and €250,000 for kettle B. Therefore, the ALLOCATION FACTOR FOR A IS 100,000€ / 350,000€ = 0.29, which means that 29% OF THE TOTAL ENERGY CONSUMPTION IN PRODUCTION ALLOCATES TO KETTLE A.

ALLOCATION DURING REUSE AND RECYCLING

The ISO 14041 standard pays special attention to ALLOCATION PROCEDURES IN REUSE AND RECYCLING. As previously stated, materials can be reused in the production of the same, or some other parts by being recycled. Component recycling means that components that have reached the end-of-life stage re-enter the production cycle after some repairs or improvements. RECYCLED MATERIALS CAUSE LESS ENVIRONMENTAL LOAD (EL) THAN THE PRODUCTION OF THE SAME MATERIALS FROM RAW MATERIALS.

The used allocation procedure in the case of recycling, especially in the case of open-loop recycling, is a challenging and difficult task since it is difficult to collect reliable and complete data. In cases of open-loop, it is difficult, and often impossible, to go backwards through the stages of material recycling. For this reason, OPEN-LOOPS ARE APPROXIMATED USING A CLOSED-LOOP MODEL. IN CLOSED-LOOP RECYCLING, IT IS ALSO ASSUMED THAT THE RECYCLED MATERIAL HAS THE SAME QUALITY AS THE VIRGIN RAW MATERIAL.

EXAMPLE OF REDUCTION OF THE ENVIRONMENTAL LOAD BY RECYCLING:

Suppose that 30% of new, unused materials and 70% of recycled materials are used in the product system. Let us further assume that the environmental load in the first phase of the life cycle, when using raw materials, is 700 Pt/kg, while the environmental load in the end-of-life phase is 600 Pt/kg, in the case of disposal and 500 Pt/kg in the case of recycling. Unit Pt/kg means Point per kilogram. The table shows the calculation comparing the environmental load in case of recycling and in case without recycling. Recycling is a practical way to reduce environmental loads.

Table 14: Allocation factor based on the sales price of the product

Life-cycle phase	**Allocation of EL due to recycling**	**EL with recycling [Pt/kg]**	**EL without recycling [Pt/kg]**
Use of raw materials (30%)	700/kg · 0.3kg = 210	210	700
EoL (disposal 30%)	600/kg · 0.3kg = 180	180	600
EoL (recycling 70%)	500/kg · 0.7kg = 350	350	0
Sum		740	1,300

HOW IS RECYCLED CONTENT ALLOCATED IN LCA ?

When allocating recycled content to LCA:

_a closed-loop recycling is assumed,

_it is assumed that the recycled material has the same quality as the virgin, raw material,
_recycled content is returned directly to the production of the same product,
_two products are compared, one with recycled content and the other without.

EXAMPLE: GLASS CUP

CUP MANUFACTURED FROM PRIMARY MATERIAL:

39. Figure_100% primary material glass cup, 500 g in weight [Source: Morris, 2007]

$E_{\text{Raw material production}}$ = 14 MJ/kg · 0.5 kg = 7 MJ

E_{Shaping} = 8 MJ/kg · 0.5 kg = 4 MJ

$E_{\text{Transport}}$ = 1.2 MJ / 1000 kgkm · 3000 km · 0.5 kg = 1.8 MJ

E_{Disposal} = 1.2 MJ / 1000 kgkm · 271 km · 0.5 kg = 0.163 MJ

The total energy consumed during the life cycle of the primary material cup is:

$E_{\text{Total}} = E_{\text{Raw material production}} + E_{\text{Shaping}} + E_{\text{Transport}} + E_{\text{Disposal}}$

= 7 + 4 + 1.8 + 0.163 = 12.963 MJ = 3.6 kWh

CUP MANUFACTURED FROM PRIMARY AND RECYCLED MATERIALS:

$E_{\text{Primary material production}}$ = 14 MJ/kg · 0,4165 kg = 5,831 MJ

$E_{\text{Recycling}}$ = 12.5 MJ/kg · 0.0835 kg = 4 MJ

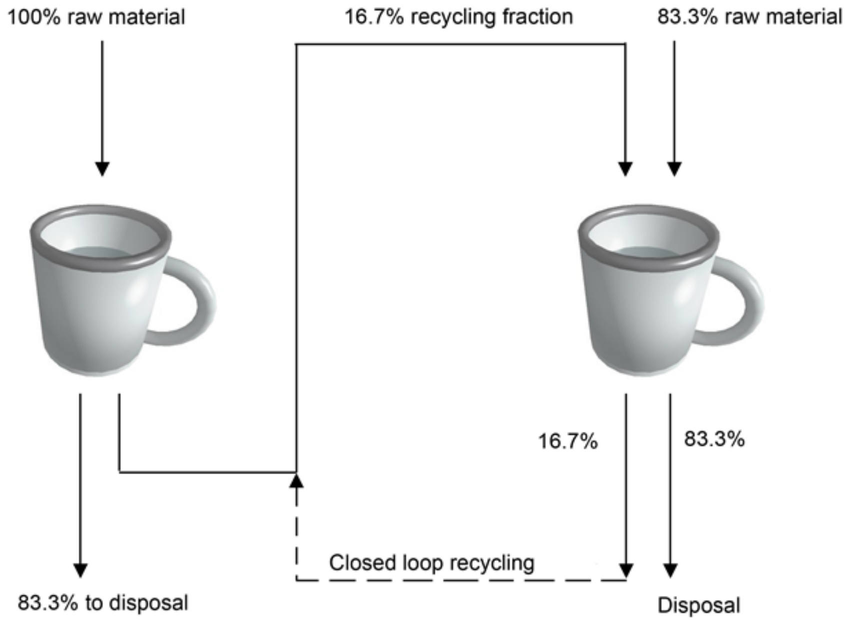
$E_{\text{Production-Total}}$ = 5,831 + 1,04 = 6,871 MJ

Energy consumed for recycling is lower than for primary material extraction. The manufacturing energy is therefore lower than in the case of a cup made of only primary material. The energies required for shaping and transport remain the same. The energy required for disposal is changed because less material is disposed of - only 83.3% (the impact of the proportion of glass products recycled in the UK, since the study was done there), instead of 100%.

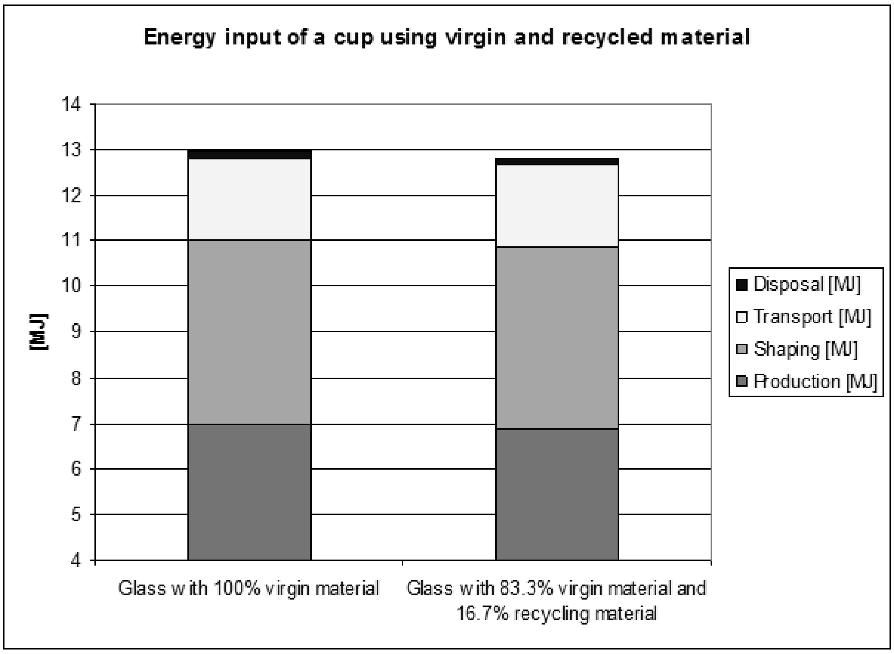
E_{Disposal} = 1.2 MJ / 1,000 kgkm · (0.0835 · 0.5 kg) · 271 km = 0.135 MJ

The total energy consumed during the life cycle of a recycled content cup:

E_{Total} = 6.871 + 4 + 1.8 + 0.135 = 12.8 MJ



40. Figure_Recycled material cup [Source: Morris, 2007]



41. Figure_Energy consumption for a 100% primary material cup and a cup with 17.7% recycled content [Source: Morris, 2007]

It may not seem like much of a difference, but if you consider producing 10,000 cups, you get a real picture of energy savings.

REFINING THE SYSTEM BOUNDARIES

The problem of defining system boundaries is, according to ISO 14041, addressed in two different phases of the LCA:

_in the “Goal & Scope Definition of LCA” phase, in the section “Scope Definition”, under the item "Initial System Boundaries”, and
_in the “LCA Inventory Analysis” phase, under the item “ Refining the System Boundaries”.

Based on the above, it is not clearly determined when and in what way the system boundaries are defined. The reason for which the final definition of boundaries is described in more detail here is that, according to ISO 14041, the boundaries are adjusted in this part, and they are often set using the material flow diagrams and process diagrams defined at this phase of LCA.

According to [VROM & CML, 2001] and [Heijungs et al., 1992], three types of boundaries can be distinguished in the LCI phase:

_boundaries between the product system and the environment,
_boundaries between significant and irrelevant processes (“cut-off”), and
_boundaries between the studied product system and other product systems (allocation).

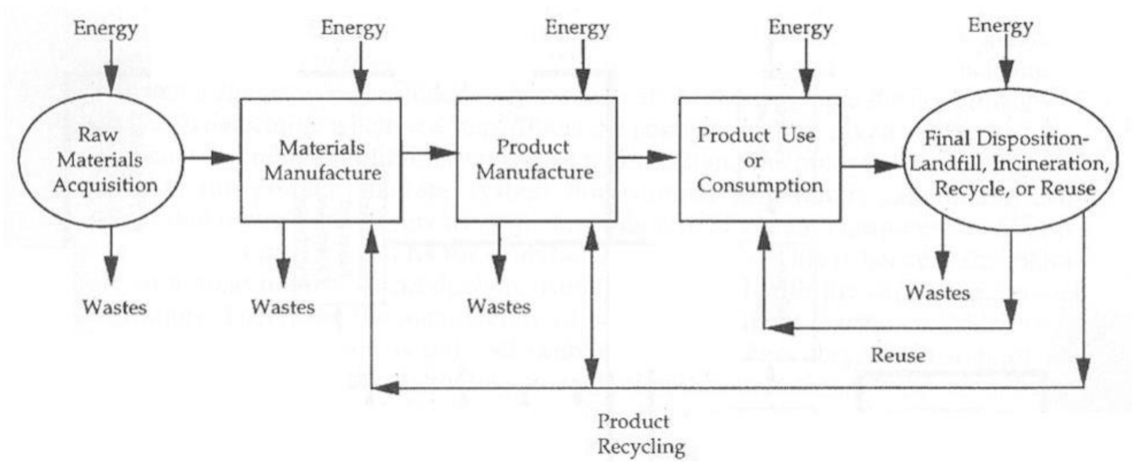
The definition of BOUNDARIES BETWEEN THE PRODUCT SYSTEM AND ENVIRONMENT is covered by the following statement:

“Ideally, the product system should be modeled in such a way that the inputs and outputs at its boundaries are elementary flows”.

ELEMENTARY FLOWS ARE DEFINED BY ISO 14040 (1997E) AS:

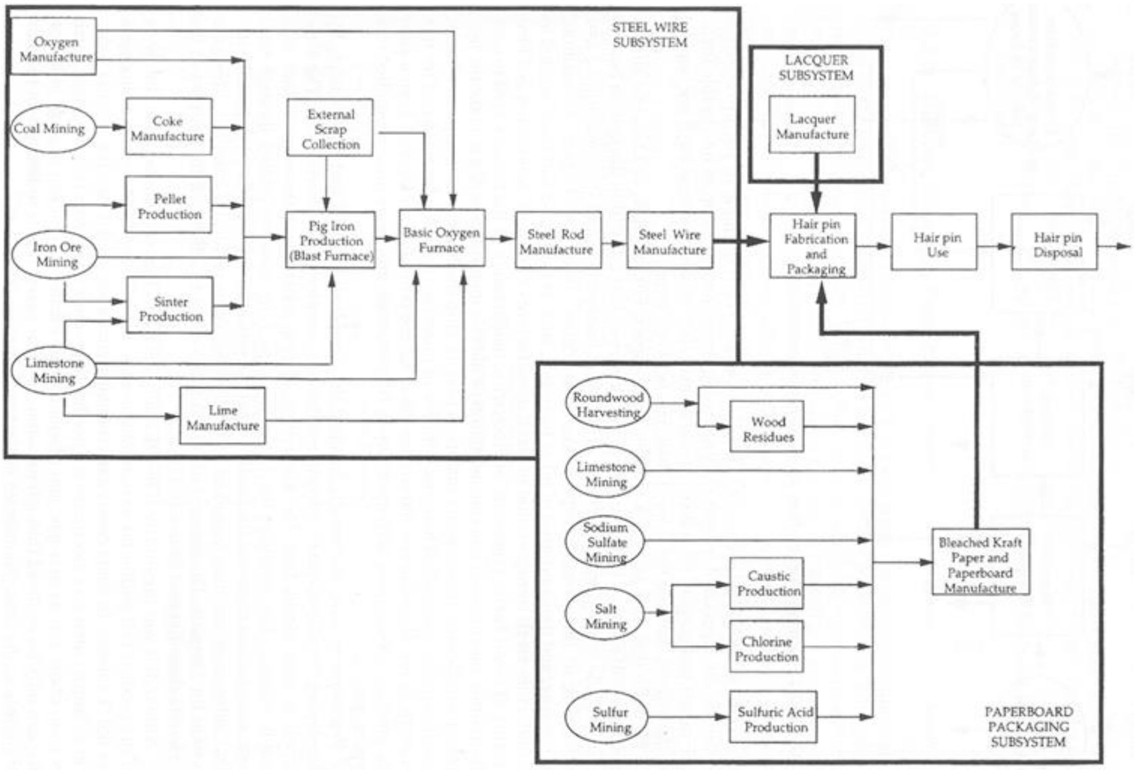
“material or energy entering the system being studied that has been drawn from the environment without previous human transformation; material or energy leaving the system being studied that is released into the environment without subsequent human transformation”.

The key point in defining elementary flow is HUMAN TRANSFORMATION.

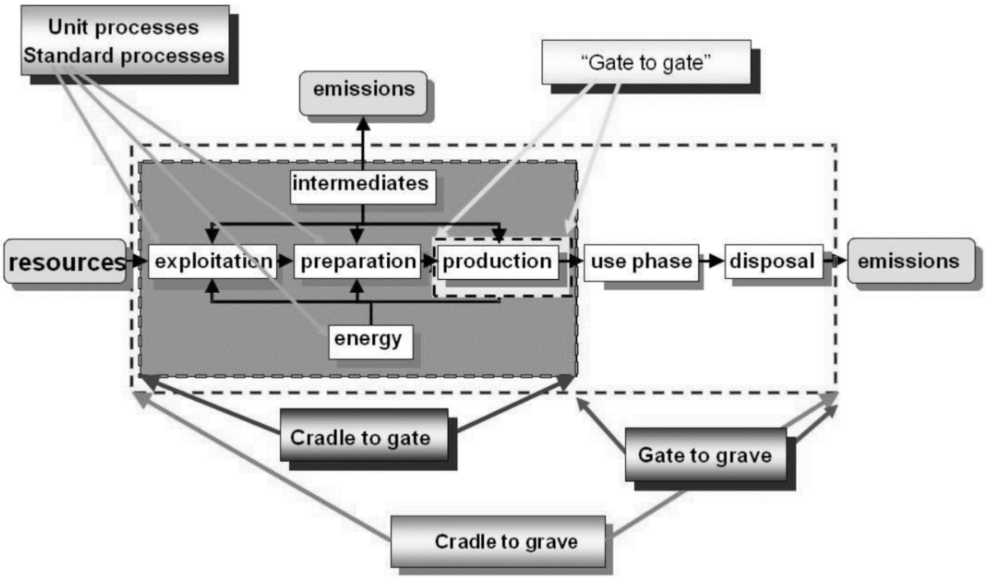


42. Figure_Material flow diagram for product lifecycle [Source: Curran, 1996]

The boundaries of a single product system are often easiest to illustrate via a MATERIAL FLOW DIAGRAM, to provide a better understanding of the processes involved [Curran, 1996]. This is a very common case, Figures 42 and 43.



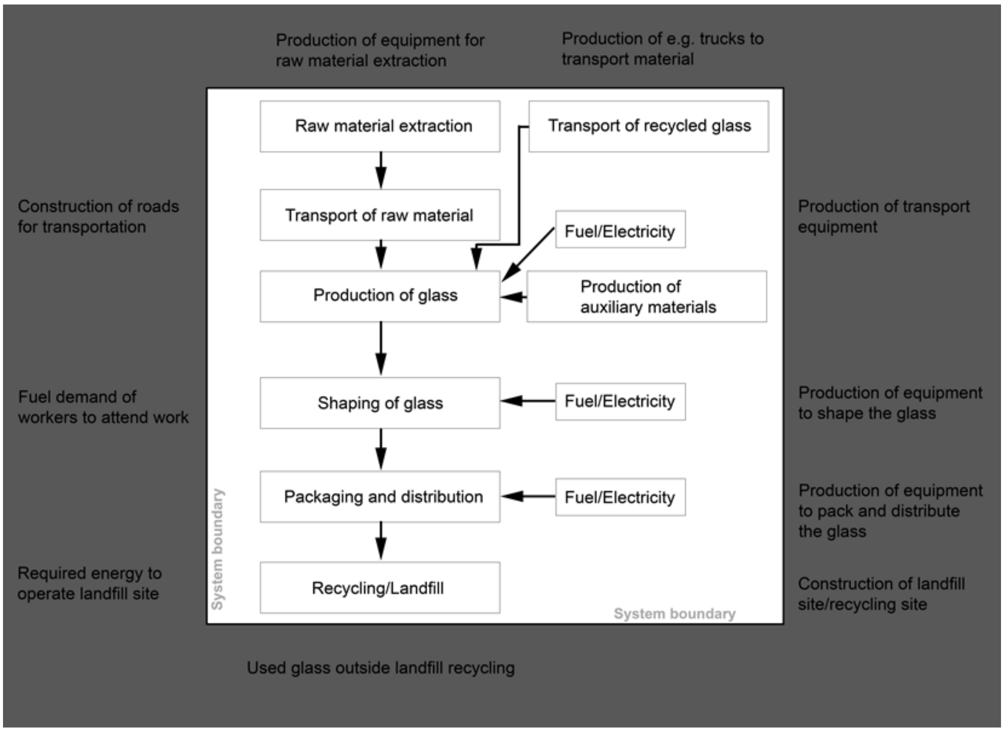
43. Figure_Material flowchart for hairpin [Source: Curran, 1996]



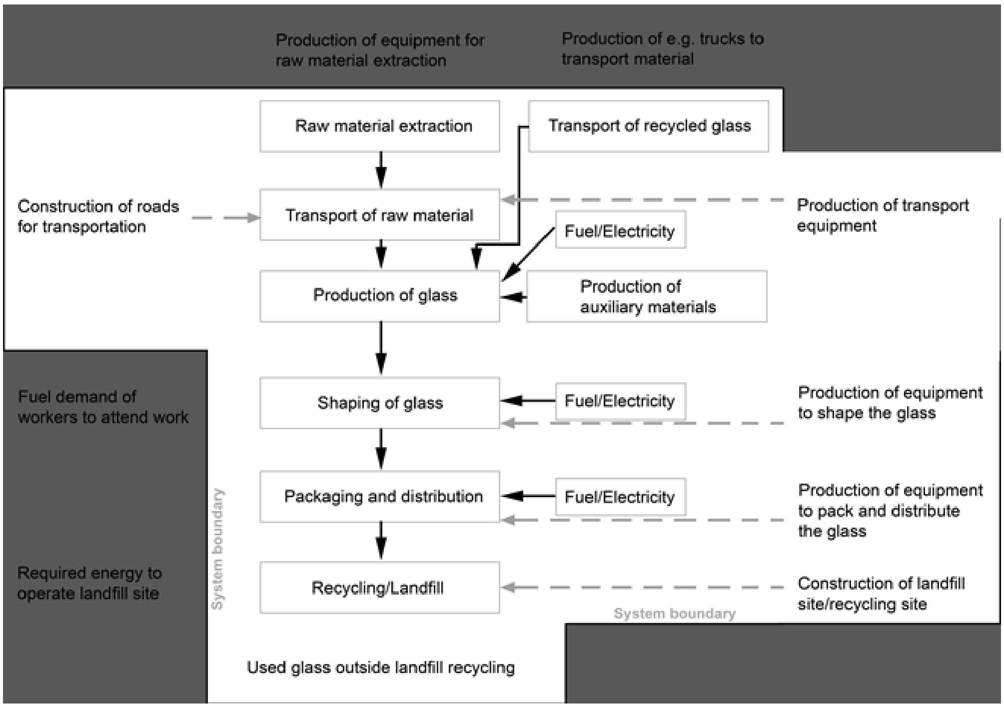
44. Figure_System boundaries [Source: GaBi Handbook PE International, 2010]

If THE BOUNDARIES CHANGE, or if another study has different system boundaries for the same product, then those STUDIES ARE NOT COMPARABLE.

Exclusion of some processes from the system without significant impact on the system is possible, but it must be performed carefully and with prior preliminary testing of the entire system (e.g. inputs and outputs in the production of capital equipment and buildings do not significantly affect the results of the LCA and are often excluded from study).



45. Figure_Example: setting the system boundaries for a glass product; white – processes included, shaded – processes excluded [Source: Morris, 2007]

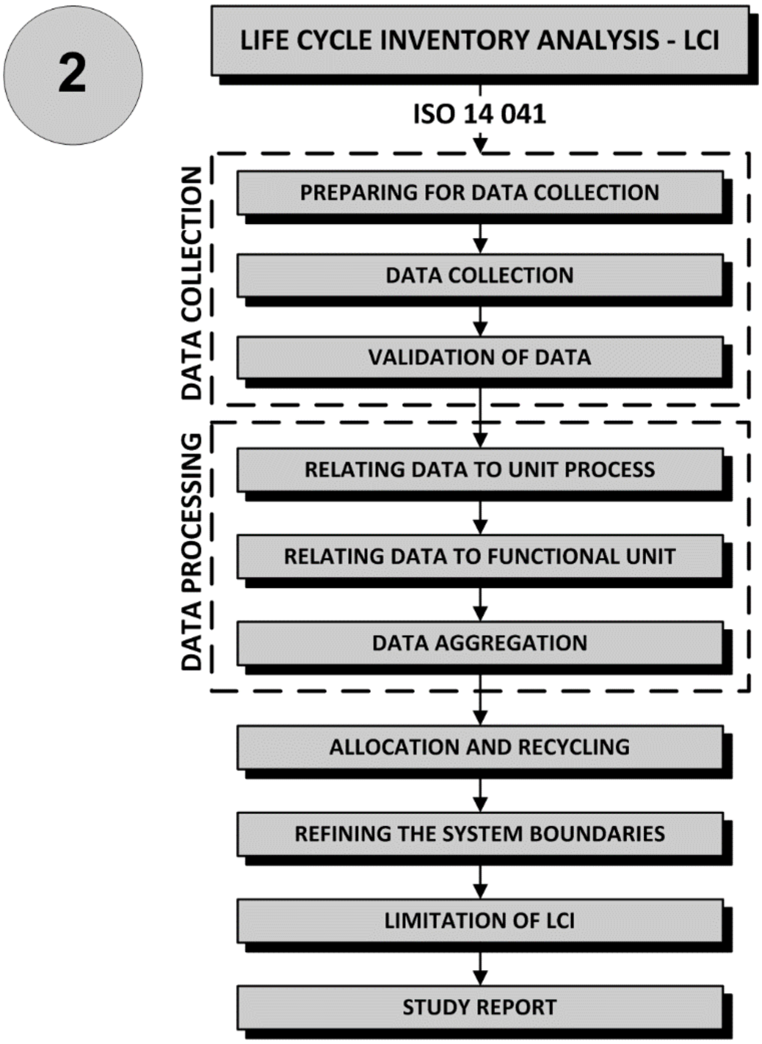


46. Figure_Example: changed system boundaries for a glass product; white – processes included, shaded – processes excluded [Source: Morris, 2007]

The main result of this phase (LCI), which is also the input for the next phase (LCIA), is the INVENTORY TABLE. When data are collected, all emissions and energy consumption of the product are tabulated at the end. The example shown in Table 15 illustrates the LCI score for CARDBOARD PACKS IN THAILAND [Ongmongkolkul & Nielsen, 2002].

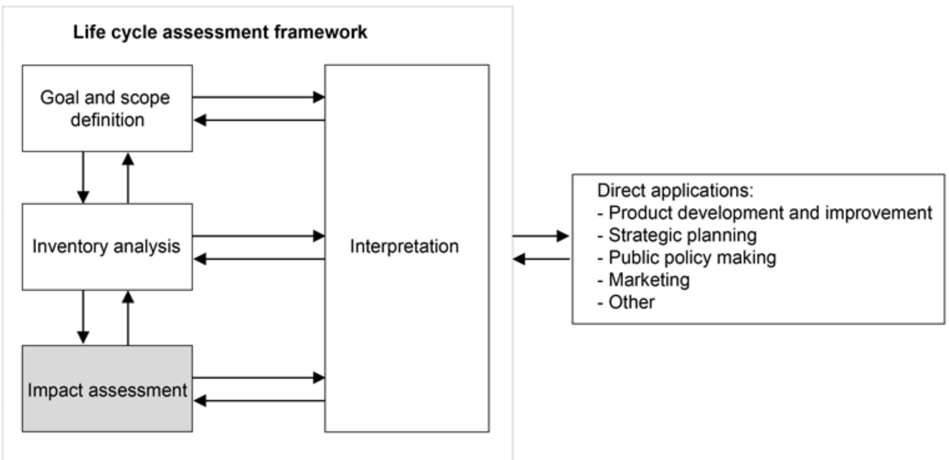
Table 15: LCI inventory table for cardboard packages in Thailand [Source: Morris, 2007]

Inputs and outputs for the selected functional unit (10 boxes)		
Inputs		
Raw materials:		
Land use for eucalyptus	2.75	m^2 per year
Wood (eucalyptus)	1.80	kg
Materials:		
Aluminum hydroxide	76.0	g
Coal	43.30	g
Crude oil	1.80	kg
Glue	7.40	g
Ink	11.30	g
Lignite	0.80	kg
Limestone	33.80	g
Lubricating oil	60.30	g
Natural gas	81.50	m3
Starch (potatoes)	12.10	g
Water	39.60	kg
Energy:	**164.00**	**MJ**
Outputs		
Product:		
Boxes	6.60	kg
Atmospheric emissions:		
CO	12.50	g
CO_2	5.10	kg
CO_2 (not from fossil fuels)	0.55	kg
H_2S	41.90	mg
CH_2	0.21	kg
NH_3	2.80	g
N_2O	0.22	g
NO_x	26.60	g
SO_x	15.20	g
NMVOC	5.90	g
VOC_s	0.21	g
Emissions to water:		
AOX	63.30	mg
BOD	0.14	g
Chlorine	11.30	g
COD	0.57	kg
Fats and oils	16.50	g
Nitrogen	0.43	g
Nitrates	0.58	g
Phosphorus	0.57	g
Sulfates	1.8	g
SS	0.40	kg
TOC	1.20	g
Solid waste generation:		
Plastic packagings	52.90	g
Waste from production	0.63	kg
Steel and metal scrap	0.15	kg



47. Figure_Inventory analysis steps according to ISO 14041 (1998E)

LIFE CYCLE IMPACT ASSESSMENT – LCIA)



48. Figure_Product life cycle impact assessment – diagram according to ISO 14040: 2006

The third phase of the LCA study ISO 14042 (2000E) is divided into the following steps:

_selection of impact categories, category indicators and characterization models,
_assignment of LCI results - classification,
_calculation of category indicator results - characterisation,
_calculating the magnitude of the category indicator results relative to reference information - normalisation,
_grouping,
_weighting,
_data quality analysis,
_limitations of LCIA,
_comparative assertions disclosed to the public,
_reporting and critical review.

The limitations of the LCIA are not specifically addressed, as they are practically covered by the limitations of the LCA, addressed in the first phase of the study. Comparative assertions disclosed to the public are one of the possible applications of LCA, and affect some choices when conducting an LCA study. The items “Data Quality Analysis” and “Report and Critical Review” are treated in the same way as in the first phase of the LCA.

In this, the third phase of the LCA study, the environmental load from the product system is converted into environmental impacts, e.g. global warming or acidification. Inventory parameters are associated with selected impact categories. This procedure represents a classification. Subsequently, the impacts of the inventory parameters are quantified into impact categories. This procedure is called characterization. For example, gases such as carbon dioxide (CO_2) and methane (CH_4), represented as parameters in the inventory data of the LCA study, are associated with the impact category GW – Global Warming. This is a step in the classification. This means that CO_2 and CH_4 gases directly affect global warming and have no effect, for example, on acidification. But CH_4 can also be associated with the impact category “photochemical oxidant creation”. This shows that certain inventory parameters may affect more than one impact category. Optional step – normalization, serves to show the regional (or global) share of modeled results in relation to the total regional (global) impacts. Finally, by means of weighting, the results of the indicator categories can be grouped their significance determined, in order to determine the social significance of different impact categories.

For the classification and characterization of impact categories, there are several different methods and two main approaches:

_PROBLEM-ORIENTED approach or MID POINT approach, and
_DAMAGE-ORIENTED approach or END POINT approach.

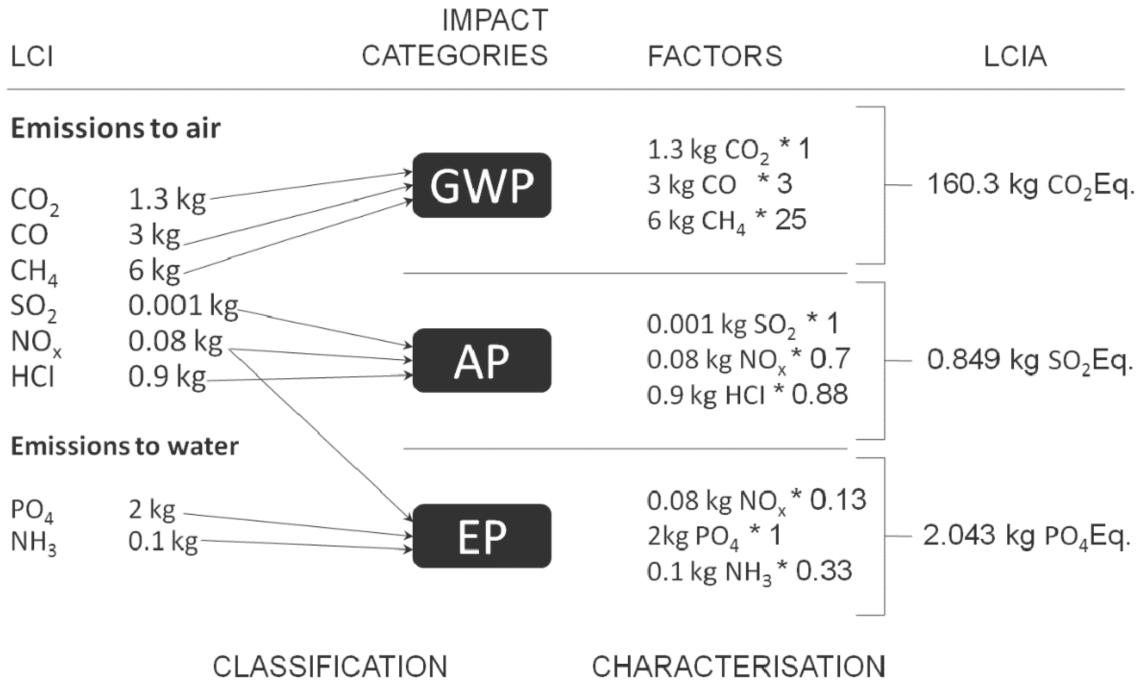
In a problem-oriented approach, flows are classified according to the group of environmental impacts to which they contribute the most. In damage-oriented methods, classification is also the first step, except that categories are being grouped according to the end result (adverse impacts on human health, ecosystem, etc.). This second approach is simpler to interpret and present.

Some of the LCIA methods are:

_CML (Leiden University, The Netherlands), problem-oriented method with GWP and ODP categories based on IPCC (Intergovernmental Panel on Climate Change) factor,
_TRACI – a problem-oriented method developed by the EPA and primarily used in the US,
_SETAC – Europe Working Group on Impact Assessment, which proposes basic impact categories and indicators of these categories, based on the “mid-point” approach,
_ECO-INDICATOR 99 (formerly ECO-INDICATOR 95), a damage-oriented method, with slightly modified impact categories compared to SETAC,
_EDIP (Environmental Design of Industrial Products) – “mid-point” approach,
_OPM (Oil Point Method), where the ENERGY INPUT is an indicator for EL – Environmental Load,
_EPS (Environmental Priority Strategies) – priority strategies for conservation of the environment, where MONETARY UNITS are taken as normalization references, etc.

In addition to these, there are special methods that take into account the REQUIREMENTS OF STAKEHOLDERS (CONSUMERS) and “translate” them into technical language. The most famous among them are:

_QFD (Quality Function Deployment) – which is an important method for integrating consumer requirements into the product development process, and
_EQFD (Environmental Quality Function Deployment), a method that helps to identify the most important environmental parameters among the many consumer requirements and stakeholder needs.



49. Figure_Example of classification and characterization [Source: GaBi Handbook PE International, 2010]

SELECTION OF IMPACT CATEGORIES, IMPACT CATEGORY INDICATORS AND CHARACTERIZATION MODELS

In order to determine the contribution of the results obtained in the second phase of the LCA to the respective impact categories, the relevant impact categories, indicators for those categories and characterization models must first be selected. Impact categories can be grouped into several different types:

_“baseline” impact categories,
_“study-specific” impact categories, and
_“other” impact categories.

CLASSIFICATION

EMISSIONS ASSOCIATED WITH IMPACT CATEGORIES

Common environmental impact categories are:

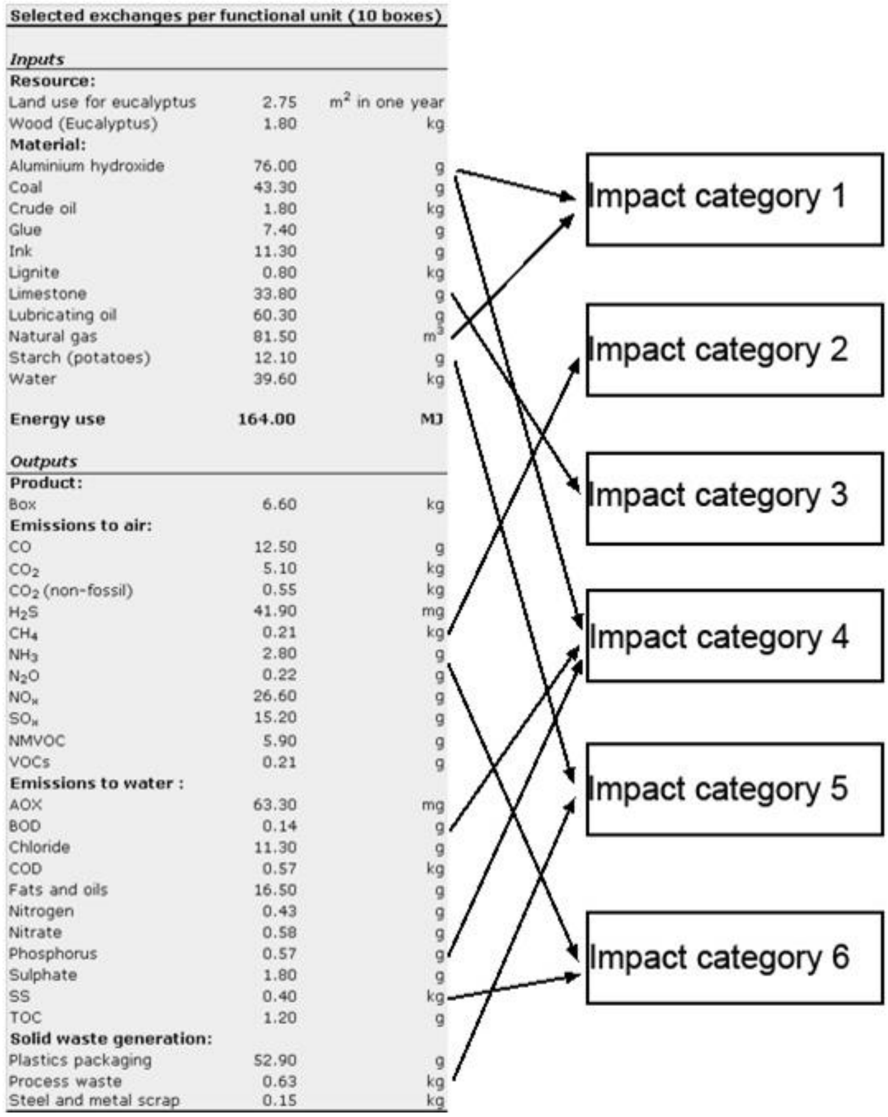
_GWP – Global Warming Potential,
_ODP – Ozone Depletion Potential,
_AP – Acidification Potential,
_EP – Eutrophication Potential,
_POCP – Photochemical Oxidant Creation Potential,
_ADP – Abiotic Depletion Potential…

How do we evaluate the given impact categories:

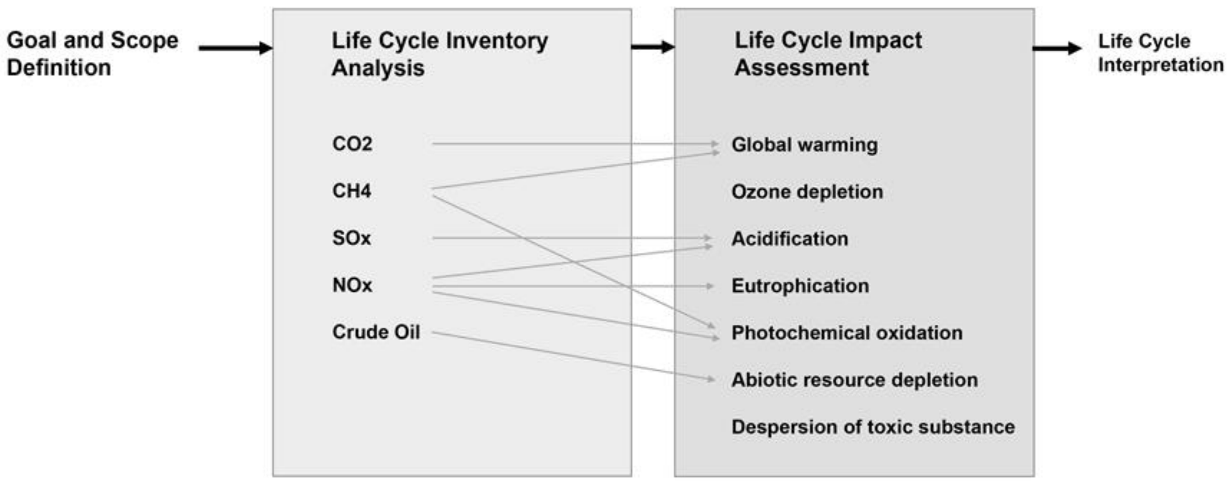
carbon dioxide and methane are in the same category - how do they relate to each other, and does one have a greater impact on the environment than the other ?

ECO-INDICATOR 99 (which was used to analyze cardboard boxes in Thailand) deals with different impact categories:

_carcinogens (substances that cause cancer),
_organic matter affecting the respiratory system,
_inorganic matter affecting the respiratory system,
_climate changes,
_ionizing radiation,
_damage to the ozone layer,
_ecotoxicity,
_acidification/eutrophication,
_land use,
_consumption of fossil fuels.



50. Figure_Classification of LCI results in the respective impact categories on the example of cardboard packagings in Thailand [Source: Ongmongkolkul & Nielsen, 2002]



51. Figure_Relation between product system output and environmental impact [Source: Morris, 2007]

CHARACTERIZATION

After classification, where each inventory parameter is related to the corresponding impact category, the RELATIVE CONTRIBUTION OF EACH OF THE PARAMETERS should be determined. Therefore, a Characterization Factor (CF) is used. In some literature, it is also referred to as the Equivalence Factor (EF). Creating a characterization factor is a difficult task. Below is shown in short lines, how to obtain the characterization factor for the impact category "global warming". First step is to identify substances that contribute to global warming - greenhouse gases. These substances are gases at normal atmospheric temperatures which are:

_able to absorb infrared radiation and are stable in the atmosphere, with a residence time of several years to several centuries,
_or are of fossil origin and can be converted to CO_2 by degradation in the atmosphere.

The greenhouse gases are of DIFFERENT TOXICITY. For example: methane is 21 times (the coefficient varies from 21 to 25 depending on the literature) more toxic than the same amount of carbon dioxide, seen over a period of 100 years.

Table 16: Overview of toxicity of greenhouse gases by global warming potential (GWP) in CO_2-eq. units [Source: IPCC - Intergovernmental Panel on Climate Change, 1995]

Gas	**Lifespan Year**	**Global Warming Potential (GWP) CO_2 equivalent units [CO_2 - eq]**		
		20 years	**100 years**	**500 years**
CO_2 – carbon dioxide	varies	1	1	1
CH_4 – Methane	12±3	56	21	7
NO_x – nitrogen oxide	120	280	310	170
HFCs –fluorocarbons		**PFCs** – perfluorocarbons		
HFC-23 – Fluoroform/ trifluoro methane/ carbon trifluoride/ Freon 23	264	9,200	12,100	9,900
HFC-125 – pentafluoro ethane	33	4,800	3,200	11
HFC-134a – tetrafluoro ethane	15	3,300	1,300	420
HFC-152a – difluoro ethane/ Freon 152	2	460	140	42
HFC-227ea – heptafluoro propane	37	4,300	2,900	950
perfluoro methane	50,000	4,400	6,500	10,000
C_2F_6 – perfluoro ethane	10,000	6,200	9,200	14,000
SF_6 – sulphur hexafluoride	3,200	16,300	23,900	34,900

The global warming (GW) characterization factor is derived from the equation:

$$CF_{GW} = \frac{\text{contribution to GW of given gas for period of T years}}{\text{contribution to GW of } CO_2 \text{ for period of T years}}$$

As can be seen from the equation, the OBSERVED TIME PERIOD OF "T" YEARS IS VERY IMPORTANT FOR DETERMINING THE CHARACTERIZATION FACTOR. The longer the time period, the lower the characterization factor becomes. A time period of 100 years is usually taken into consideration. THE EQUATION ALSO SHOWS THAT CO_2 GAS IS TAKEN AS THE BASIS FOR QUANTIFYING GLOBAL WARMING, AND IN ORDER TO COMPARE THESE GASES IN TERMS OF TOXICITY, THE "CO_2-eq UNIT" WAS INTRODUCED**.** In other words, the impact of all other gases on global warming is compared with CO_2. This means that the CO_2 GAS HAS A CHARACTERIZATION FACTOR OF 1, as well as:

_CO_2 and CH_4 have different impacts on global warming,
_methane is more dangerous than carbon dioxide,
_a small amount of methane has a major impact on global warming,
_1 g of methane in the atmosphere has the same effect on global warming as 21-25 g of carbon dioxide for the observed period of 100 years.

Table 17: Units for environmental impact categories according to the EDIP method [Source: Wenzel, 2000]

Environmental impact category	**Unit**
Global warming	[g CO_2 - eq]
Ozone layer depletion	[g CFC 11 - eq]
Photochemical ozone formation - smog	[g C_2H_4 - eq]
Acidification	[g SO_2 - eq]
Eutrophication (nutrient enrichment)	[g NO_2 - eq]
Ecotoxicity, water, chronic	[m^3] of water
Human toxicity, water	[m^3] of water
Ecotoxicity, water, acute	[m^3] of water
Human toxicity, air	[m^3] of air
Hazardous waste	[g]
Nuclear waste	[g]
Slag and ash (inert waste)	[g]
Bulk waste	[g]

The Characterization Impact (CI) of an inventory parameter is obtained by multiplying the Environmental Load (EL) of that parameter by the corresponding Characterization Factor (CF).

Computation of the CI for the inventory parameter (e.g. CH_4) is derived from the equation:

$$CI = CF \cdot EL$$

The equation shows that the CI UNIT DEPENDS ON THE IMPACT category. In the case of global warming, the unit would be g CO_2 - eq, where eq represents the "EQUIVALENT", leaving the impression that this factor indicates the contribution of inventory parameters to global warming equal to the contribution of CO_2.

The same thing that applies to global warming can also be applied to other impact categories, such as "ozone depletion", "acidification", "eutrophication", "photochemical oxidant creation" and "abiotic resource depletion". Appropriate characterization factors of inventory parameters can be found in the literature.

Table 18 shows the classification and characterization carried out on the example of the already mentioned cardboard packagings in Thailand. The inventory analysis was carried out with the software package Sima Pro (VERSION 4), and the method used for impact assessment is ECO-INDICATOR 95, the earlier variant of ECO-INDICATOR 99 method.

Table 18: Impact Categories of cardboard boxes in Thailand [Source: Ongmongkolkul & Nielsen, 2002]

Impact category	Quantity per functional unit [10 boxes]	Unit
Global warming	7.47	kg CO_2 - eq
Acidification	43.1	g SO_2 - eq
Eutrophication	20.2	g PO_4 - eq
Smog	5.64	g C_2H_4 - eq
Solid waste generation	0.91	kg
Damage to the ozone layer	0.57	g COD

NORMALIZATION

In order to be able to compare individual contributions of different environmental impact categories, we perform NORMALIZATION.

Standard ISO 14042 (2000E) defines NORMALIZATION as:

"calculating the contributions of indicator results relative to REFERENCE VALUE – NORMALIZATION REFERENCE".

The normalization reference may be related to a given society (e.g. The Netherlands, Europe or the world), a person (e.g. a citizen of Denmark) or another system, in a given period of time.

A particular IMPACT MAY HAVE A LOCAL, REGIONAL or GLOBAL IMPACT, depending on the impact category. Global warming is a global impact, while acidification is regional and smog is local. In a certain geographical region there are impacts from other products as well. For global impact categories, such as global warming and ozone depletion, the GLOBAL BACKGROUND LOAD is used as a normalization reference. For regional and local environmental impact categories, the DANISH BACKGROUND LOAD is used. For global as well as for local environmental impact categories, the YEAR 1990 was taken as a REFERENCE.

The sum of the impacts of all products determines the environmental impact of the region. The fractional contribution of the product's impact to the total impact of all products in geographical region is called the Normalized Impact – NI.

$$\mathbf{NI} = \frac{\mathbf{CI}}{\mathbf{N}}$$

In order to be able to calculate the normalized impact, a Normalization Reference (N) is required.

The Normalization Reference (N) is the sum of all impacts of a certain impact category from all products in a certain region. The unit for N depends on the impact category.

$$N = \sum \frac{(\text{load of parameter per year}) \cdot (CF \text{ of parametar})}{\text{population of geographic region}}$$

NORMALIZATION ALLOWS DIRECT COMPARISON OF VALUES OF DIFFERENT IMPACT CATEGORIES. This is possible because all impact categories are considered to have the same significance.

GROUPING

Grouping is a step of the LCIA phase in which impact categories are combined into one or more sets. It is an optional element for which two possible procedures are available:

_SORTING – based on characteristics such as emissions and resources, or global, regional and local impacts, and
_RANKING – of the category indicators on an ordinal scale, e.g. a given order or hierarchy, such as high, medium or low priority.

WEIGHTING

For a more realistic presentation, the assumption that all impact categories have the same significance must be discarded. Depending on social, ethical, political or other values, different impact categories bear different significance. WEIGHTING ALLOWS CASING THESE DIFFERENT SIGNIFICANCES.

The Weighted Impact (WI) can be expressed as follows:

$$WI = \sum (\text{weight of given impact category}) \cdot (NI \text{ of that impact category})$$

THE WEIGHTED IMPACT OF A PRODUCT is obtained by summarizing all weighted impacts of the different impact categories:

$$WI_{\text{product}} = \sum WI \text{ of each impact category}$$

The equation shows that A FACTOR IS REQUIRED TO DETERMINE THE WEIGHT OF AN IMPACT CATEGORY. Three methods of measurement are presented in the literature. These methods are:

_panel method,
_monetization method,
_target method.

In the PANEL METHOD, a group of people, who are representatives of society, give their opinion on the relative importance of the impact category. Group members determine the importance of impact categories based on four elements, namely:

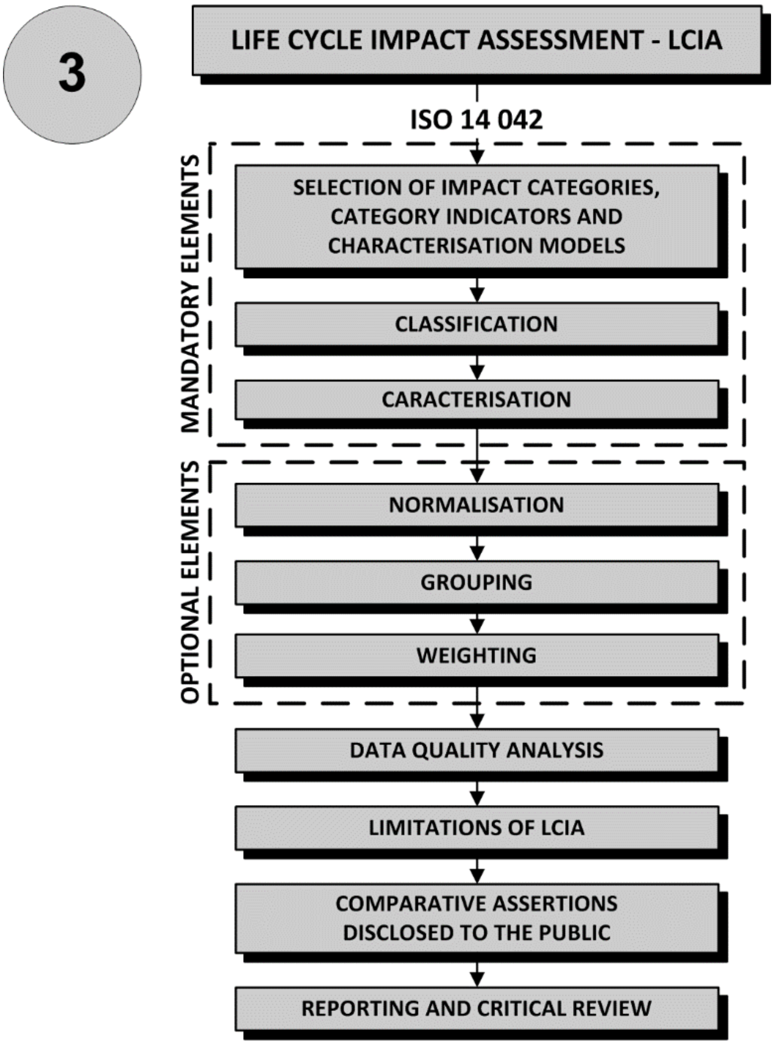
_degree of scientific uncertainty,
_duration of impact,
_degree of irreversibility,
_scale of impact.

This means that impacts with unknown consequences are considered more seriously than those with scientifically known consequences. Long duration impacts are more important than short duration impacts; irreversible impacts are more serious than reversible impacts. Global impacts have a higher weight factor than regional and local impacts.

In the MONETIZATION METHOD, a group of people were asked to assign monetary values to different impact categories. This method measures the willingness of the society to pay in order to avoid damage from impact.

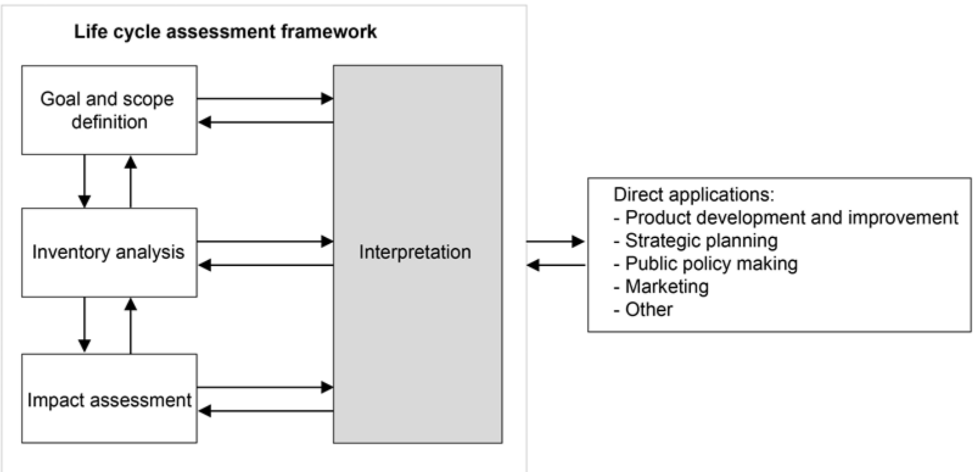
In the TARGET METHOD, the relative significance is related to some type of impact category target, e.g. political targets and goals. In this method, the distance between the "status quo" and the target impact level is estimated.

Finally, it should be noted that according to ISO 14042 (2000), the WEIGHTING IS NOT ALLOWED IF TWO PRODUCTS NEED TO BE COMPARED.



52. Figure_Steps of the life cycle impact assessment phase according to ISO 14042 (2000E)

LIFE CYCLE INTERPRETATION



53. Figure_Llife cycle interpretation – diagram according to ISO 14040: 2006

The fourth and final step of the LCA study, called LIFE CYCLE INTERPRETATION, is explained in ISO 14043 (2000). The life cycle interpretation consists of the following steps:

_identification of significant issues, based on the results of the LCI and LCIA,
_evaluation, comprising completeness, sensitivity and consistency checks,
_conclusions, recommendations and reporting.

Other elements of the analysis, including critical review, are covered in the appendix by clause 9 of ISO 14043 (2000).

The fourth phase of the LCA study is carried out after each of the previous phases and includes an interpretation of the results, which can provide feedback regarding the previous phases (iterative process) and enable potential improvement.

ISO 14043 (2000) introduces a method called "CONTRIBUTION ANALYSIS" to find out the key issues and weak points of the product. The characterized impact results are expressed in a matrix where rows show inventory parameters and columns show unit processes and activities. Such a matrix can be calculated for each impact category. As an example, Table 19 for the global warming impact category is shown, where two parameters of the CO_2 and CH_4 inventory are shown in two rows, and five life cycle phases are shown in five columns.

Table 19: Matrix of characterized impact results

	Material	Manufacture	Distribution	Use	EoL	Sum
CO_2	R1	M1	D1	U1	E1	S1=R1+M1+D1+U1+E1
CH_4	R2	M2	D2	U2	E2	S2=R2+M2+D2+U2+E2
Sum	R1+R2	M1+M2	D1+D2	U1+U2	E1+E2	S1+S2

The unit of input in Table 19 is g CO_2 - eq. Each input into the matrix is divided by the total impact of the product system (S1+S2) and expressed as a percentage of the total. Now that these values are available in percentages, it is important to define "CUT-OFF" limits. For example, if the limit is set to 2%, all contributions lower than that value are ignored. What remains are the KEY ISSUES.

The aim of the COMPLETENESS CHECK is to control and evaluate whether the LCA study covers all important data and whether they are complete or not. If not, certain actions must be taken.

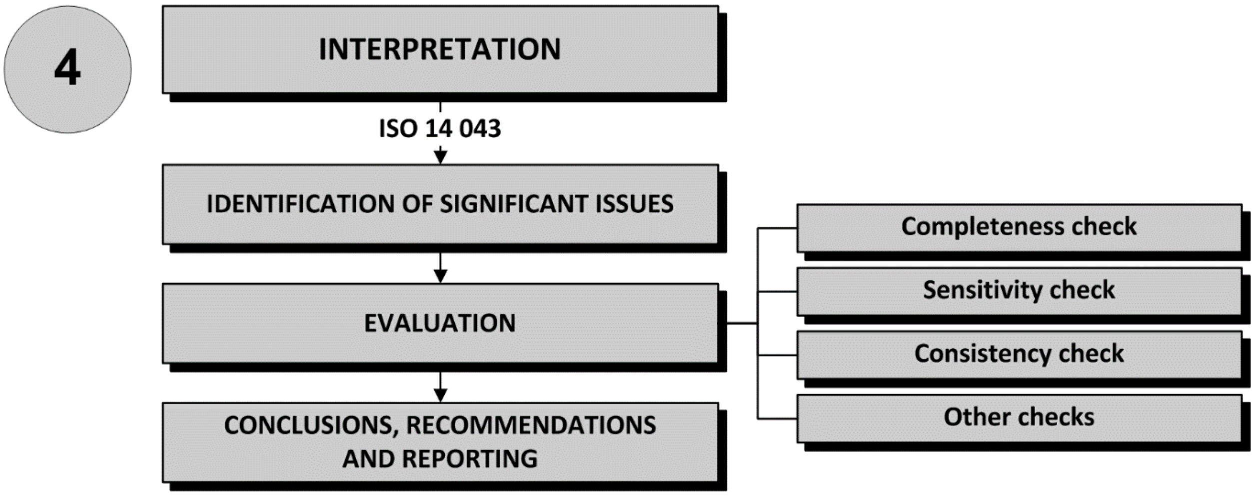
The SENSITIVITY CHECK assesses the impacts of process data variations, model selection and other variables on the results of the study. These variations are deliberately made in the sensitivity check in order to determine the robustness of the results in view of these variations. "SENSITIVITY" can be defined as the percentage change or absolute deviation of results in case of a change in the range of parameters, data and assumptions.

The CONSISTENCY CHECK is used to determine whether assumptions, methods, models and data are consistent at all times with the goal and scope definition of the LCA study.

A CRITICAL REVIEW of the LCA study is explained in ISO 14040 (1997). The objective of the critical review is to assess whether the LCA study meets the criteria described in ISO standards, to evaluate the scientific methods used in the LCA study, and to assess data quality and documentation transparency. CRITICAL REVIEW CAN BE PERFORMED BY AN EXPERT WITHIN THE COMPANY WHO DID NOT PARTICIPATE IN THE LCA STUDY OR BY AN EXTERNAL INSTITUTION. This external institution may be an expert or a group of people interested in LCA studies.

If the results are error-free, a FINAL REPORT can be organized showing the results and assumptions. The report must be written in relation to the audience of the LCA study. Environmental Product Declaration – EPD IS A STANDARDIZED WAY OF WRITING SUCH A REPORT FOR CUSTOMERS.

Now that the results of the LCA study have been achieved and weak points and key issues have been identified, RECOMMENDATIONS FOR THE IMPROVEMENT OF THE PRODUCT can be suggested.



54. Figure_LCA final phase steps according to ISO 14043 (2000)

LCA METHODS AND TOOLS

OVERVIEW OF LCA METHODS AND SOFTWARE TOOLS

To design better products, we need adequate and efficient tools. There are various methods, approaches and tools for calculating environmental impacts, starting from guidelines and recommendations, through checklists and indicators to complete LCA studies, which include methodologies, process simulations and extensive databases for materials and processes. In a broad sense, ecological assessment tools require measuring the impact of a product on one or a combination of the following factors (always including ecology):

_society,
_economy,
_ecology.

The results of a research conducted in 2006 and a survey of designers applying the LCA method intensively showed that the LCA method is applied for:

_support to business strategies – 18%,
_R&D – 18%,
_product design process – 15%,
_education – 13%,
_declarations and marking of products – 11%,
_other – 25%.

The same research has shown that the software tools most commonly used for LCA studies are:

_GaBi SOFTWARE, developed by "PE INTERNATIONAL" (Stuttgart - Germany) – 63%,
_SimaPro, developed by "PRé COSULTANTS" (The Netherlands) – 31%; this company, in addition to the SimaPro software package, developed the Eco-indicator 99 method for LCIA, which is generally accepted in the EU,
_other tools – 6%.

[Vujičić, 2010], [GaBi Handbook PE International, 2010]

GABI AND SIMAPRO

GaBi tools for optimizing the environmental impact of products and processes include:

_GaBi 4 – standard software for life cycle assessment in all areas,
_GaBi DfX – for analysis of recyclability potential and compliance with laws,
_GaBi LITE – LCA and DfE (Design for Environment) software tools for beginners.

GaBi 4 supports all phases of the LCA study, from data collection to organizing the presentation of results. The software automatically finds appropriate materials, energy and emission flows, defined economic values, working hours and social components, thus providing an immediate possibility to calculate a large number of environmental impact categories. In addition to the modular and parameterized architecture, this platform is supplied with the largest and most relevant database for LCA. The database contains over 2,000 "cradle-to-gate" processes related to materials, 8,000 chemical processes and thousands of LCA projects implemented by the quality management of industrial companies.

SimaPro is a software for a complete LCA study. Complex products with complex life cycles can be compared and analyzed. Process databases and impact assessment databases can be modified and expanded indefinitely. The ability to trace the origin of any result has been implemented in a very flexible and powerful way. Special additions are:

_multiple impact assessment methods,
_multiple process databases, automatic unit conversion.

Moreover, there are powerful tools for analyzing the refurbishment of waste products and their disassembly, as well as complex waste treatment and recycling scenarios. The LCIA methods covered by the SimaPro tool are:

_ReCiPe,
_BEES,
_Eco-indicator 99,
_Eco-indicator 95,
_CML 92,
_CML 2 (2000),
_EDIP/UMIP,
_EPS 2000,
_Ecopoints 97,
_Impact 2002+,
_TRACI,
_EPD method,
_Cumulative Energy Demand,
_IPCC Greenhouse gas emissions.

[http://www.earthshift.com/software/simapro/impact-assessment-methods]

IVAM LCA DATA is a database in SimaPro 7 format for further use in LCA studies [http://www.ivam.uva.nl/index.php?id=164&L=1&L=1]; SimaPro 8 uses ECOINVENT 3 DATABASE.

OTHER TOOLS AND METHODS OF LCA AND LCIA

Other tools and methods for LCA and LCIA include:

_EDIP PC-TOOL, a user-oriented software package developed by the Ministry of environment of Denmark with an inventory database in SPOLD format,

_ECO-INDICATOR is primarily a tool for designers. Allows designers to conduct their own LCA study with the help of 100 predefined LCAs for commonly used materials and processes. The designer can use the ECO-INDICATOR in two ways: 1) **to correctly ask questions** (what are the root causes of environmental load from the product), and 2) **to get the right answers** (which alternatives in product design have the least impact on the environment). The methodology builds on the SETAC LCA methodology - it uses normalization and weighting. PRODUCT ECOLOGY CONSULTANTS provide a list of existing ECO-INDICATORS,

_CMLCA, software developed at the University of Leiden (Netherlands) based on the CML methodology,

_Dubo-Calc**.**, a database created by Ministry of transport of the Netherlands, containing information on materials used in public works.

_UMBERTO is a diverse and flexible tool for LCA study and eco-balancing based on unique methods and Material Flow Networks (MFNs). The comprehensive database contains predefined transition modules (raw materials, materials, manipulation processes, waste processing, etc.),

_LCAiT, produced by "CIT ECOLOGIC", saves time for the user when generating and solving material balances. It allows sensitivity analysis by allowing the user to generate multiple alternative solutions for only a part of the time it would take to do it manually. The documentation is structured according to the life cycle. The accompanying text can be added to the data in all fields. The software is easy to use and compatible with MS WINDOWS environment. The software package forms flowcharts, using "tabs" for processes and transport, which are simply connected by clicking and dragging. Clicking on the "tab" opens a "window" in which the parameters can be modified. One process "tree" can be imported into another LCA file, thus establishing a modular design. The results of one LCA study can be imported into the "tab" within another LCA study. This opens up the possibilities of unifying the LCA study. The results are displayed as block diagrams, easy to read (interpret) and modify. The results can be exported to MS EXCEL or similar software for further analysis or text processing,

_TEAM software package by PRICEWATERHOUSE COOPERS ECOBILAN GROUP is a professional tool for assessing the life cycle and costs of products and technologies. It contains an extensive database with over 600 modules.

_BEES (Building for Environmental and Economic Sustainability), a software tool developed by the National Institute for Standards and Technology (NIST) uses the SETAC method for classification and characterization of six categories of impacts (global warming, acidification, eutrophication, depletion of natural resources, solid waste and indoor air quality).

_BOUSTEAD MODEL, by BOUSTEAD, is a database of fossil fuel combustion impacts, resources, exhaust emissions, etc.,

_ECOINVENT DATABASE contains over 2,700 data groups for the territory of Switzerland, Europe and the world, over 1,000 elementary flows and several inventory databases,

_ECO-QUANTUM is a tool for calculating the environmental impact of newly built buildings. It contains over 1,000 examples, but is only available in Dutch,

_ENVIRONMENTAL IMPACT INDICATOR is a program for LCA analysis of residential buildings, intended for architects, engineers and research. Contains an inventory database with over 90 structural materials.

_EPS 2000 (Environmental Priority Strategies in product design), Sweden - the tool is intended primarily for the development of products within companies. EPS 2000 tool is an upgrade to the 1996 version.

_GEMIS is a database developed by the German Ecological Institute,

_GREET model was developed by the U.S. Department of energy and transportation to evaluate new fuels and technologies in the automotive industry,

_KCL-ECO is a LCA tool for complex systems with a lot of modules and flows,

_LCAPIX by KM LIMITED connects LCA and costing activities to help align environmental standards and profitability,

_MIET (Missing Inventory Estimation Tool), developed by CML, is actually MS EXCEL database, which allows determination of missing LCA inventory streams,

_REGIS is a software made by the German company SINUM AG. It is used to create corporate eco-balances and improve business operations complying ISO 14031 standard,

_US LCI data is an inventory database covering the public and private sectors. It is based on ISO 14048 and compatible with ECOSPOLD format**,**

_AUDIT is a program of modular structure for environmental management and control, as well as analysis and simulation of complex systems. As a comprehensive program for the balance of material flows, AUDIT can be applied to all processes and material flows within a given company,

_Design For Manufacture and Assembly - DFMA, design, assembly and disassembly software, by BOOTHROYD DEWHURST, INC., is a combination of two complementary tools: Design for Assembly (DfA) and Design for Disassembly (DfD),

_International Dismantling Information System **–** IDIS – is a software developed to optimize and facilitate the recycling of End-of-Life Vehicls (ELVs). It is designed to provide an overview of data and manuals related to the end of the vehicle life cycle,

_WUPPERTAL INSTITUTE FOR CLIMATE, ENVIRONMENT AND ENERGY: MIPS of the Wuppertal Institute focuses its work on application-oriented sustainability research,

_NATIONAL INSTITUTE FOR MATERIALS SCIENCE, Japan contains a database of materials for LCA,

_LCA HOTLIST is a set of information and links related to the LCA study, collected and annotated by G. Doka,

_A GUIDE FOR ECODESIGN TOOLS contains a list of some LCA tools with a short description...

Among the most commonly used LCIA methods, which will be explained later, are:

_ECO-INDICATOR 99 [Goedkoop, 2001],
_EDIP **-** Environmental Design of Industrial Products [Wenzel, 1997],

and methods that take into account both consumer requirements and “translate” them into technical language:

_QFD (Quality Function Deployment),
_EQFD (Environmental Quality Function Deployment).

APPLIED LCA METHODS

Since the LCA study is cumbersome (a lot of data), time-consuming and expensive, many simplified methods for LCA analysis have been developed.

TWO APPROACHES CAN BE SINGLED OUT FOR A SIMPLIFIED LCA:

1. qualitative description of the product,
2. quantitative description of the product.

Among the simplified LCA methods are:

_Qualitative assessment of the product (Description),
_MET MATRIX (Material, Energy, Toxicity Matrix) - represents a matrix whose columns form life cycle phases of a product (all 5), and rows represent material, energy and toxicity,
_ECOLOGICAL FOOTPRINT represents a measure of human demand from the planet Earth's ecosystems,
_ECOLOGICAL RUCKSACK – it is assumed that each product carries a certain ”ECOLOGICAL BURDEN” in a theoretical “RUCKSACK”,
_MIPS (Material Input Per Service or Material Intensity Per Unit of Service) –Material input per operation – material flow is the main category of damage,
_CHECK LISTS – lists compiled to provide the concept of sustainability; usually they can be a part of a more comprehensive tool,
_ECODESIGN WEB virtually represents a visual check list,
_ECO-EFFICIENCY[7] – assessment of the product according to the number of performance parameters. Different methodologies are used depending on the different distributors,
_ECO-IT TOOL – Tool developed by the LCA software developer, intended especially for product designers. It's a simplified version of LCA, which uses ECO-INDICATOR 99 as the LCIA method,
_ECOTOXICITY – the percentage of all species in a given region that are under **toxic stress**, expressed as a fraction (portion) – there have been attempts to align this with product design,

[7] *The concept of Eco-efficiency is based on the use of resources with the aim of economic and environmental progress, through the efficient use of resources and the reduction of pollution [United Nations ESCAP, 2009].*

_EMBODIED ENERGY, explained by a simple definition: “the amount of energy accumulated in the product during the production process and at all other stages of the life cycle, excluding the use phase”,
_FULL COST ACCOUNTING / ACTIVITY BASED COSTING - accounting techniques, which not only pay attention to profit and loss, but also to environmental factors,
_GREEN INDICES / INDEX REPORTS – indicators of environmental parameters can be used as an existing benchmark. However, it is sometimes not easy to determine how to calculate indices (indicators),
_MASS BALANCE SYSTEM – examines the input and output of energy and materials in a process or product. It is presented by the equation,
_MATERIALS FLOW ANALYSIS – includes monitoring and assessment of the system based on testing of internal and external economic and environmental flows and exchanges.
_ECODESIGN ASSISTANT (http://www.ecodesign.at/assist/assistent?lang=en),
_ECODESIGN PILOT (Product Investigation, Learning and Optimization Tool) (http://www.ecodesign.at/pilot/ONLINE/ENGLISH/), PILOT and ASSISTANT are mutually complementary simplified LCA methods. They do not provide a quantitative output, but only a relative comparison of environmental impacts of individual stages of the product life cycle.

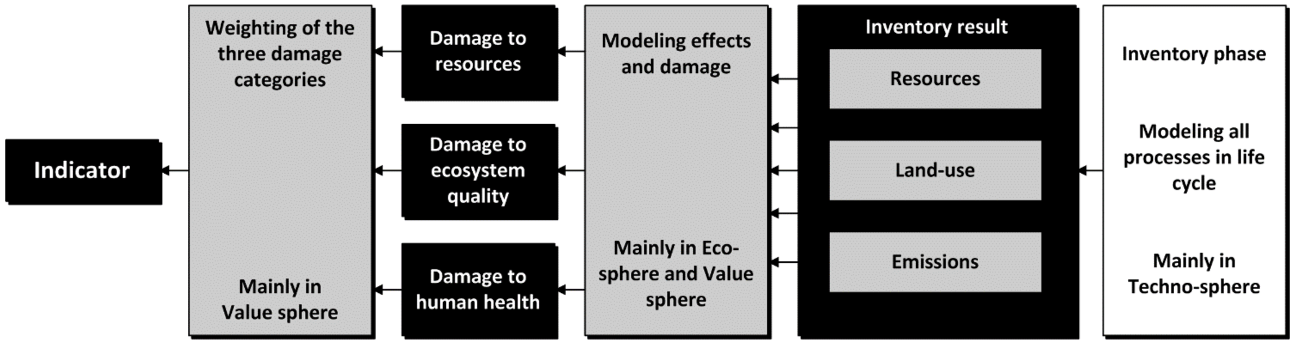
ECO-INDICATOR 99

ECO-INDICATOR 99 is a damage-oriented METHOD of assessing the environmental impact of a product during its life cycle. ECO-INDICATOR 99 considers three categories of damage:

1. human health;
2. ecosystem quality,
3. resources.

In the LCA study there are three spheres of scientific knowledge and reasoning:

_TECHNO-SPHERE, in which the life cycle is described (leads to an inventory of results),
_ECO-SPHERE, in which environmental damage is modeled (linking the inventory of results to three categories of damage),
_SPHERE OF VALUES, where the severity of damage is modelled (weighting three categories of damage into one indicator).



55. Figure_Generation of a single indicator with the help of different spheres [Source: Goedkoop et al., 2001]

To accurately define the results of the LCA study, it is also necessary to define THE "ENVIRONMENT". According to [Goedkoop et al., 2001], the ENVIRONMENT is defined as:

"A set of biological, physical and chemical parameters influenced by man, that are conditions to the functioning of man and nature. These conditions include human health, ecosystem quality and sufficient supply of resources."

HUMAN HEALTH

This category of damage implies that the health of any person, current generation or future generations, can be damaged by SHORTENING THE LIFE SPAN, sudden DEATH, or limiting bodily functions, so-called DISABILITY. Damage to human health is expressed in Disability Adjusted Life Years (DALY). The models for this damage category have been developed based on the following impacts (impact category):

_effects of ozone layer depletion (causing eye damage and cancer),
_climate change (causing infections and respiratory diseases),
_ionizing radiation (causes cancer),
_toxic substances in air, water and food (causing respiratory diseases and cancer).

Models of damage to human health are formed through four steps of analysis:

1. FATE ANALYSIS, linking emissions to temporary changes in concentration,
2. EXPOSURE ANALYSES, linking the temporary concentration to dose,
3. EFFECT ANALYSIS, linking the doses to the number of health effects,
4. DAMAGE ANALYSIS, linking the health effects with DALY, using the Years of Life Disabled (YLD) and Years of Life Lost (YLL) assessment.

The core of the human health damage unit, DALY, is a SCALE OF SIGNIFICANCE, containing a list of various damages in the range of 0-1 (0 - perfectly healthy, 1 - death).

ECOSYSTEM QUALITY

Ecosystem quality damage is expressed as a PERCENTAGE OF EXTINCT SPECIES, which have disappeared in a given region, due to the environmental load caused.

BIODIVERSITY is used as an indicator for ecosystem quality, not individual organisms. In this case, the following impacts are taken into account:

_ecotoxicity – percentage of all species in the region exposed to toxic stress,
_acidification and eutrophication – treated as one impact category,
_land use and transformation, where local damage to the occupied land is taken into account, as well as global damage to the ecosystem.

ECOTOXICITY - TOXIC STRESS

For ECOTOXICITY, a method is used that determines the Potentially Affected Fraction (PAF) of species relative to the concentration of toxic substances. PAF is determined on the basis of toxicity data for organisms in water and on the ground, and expresses the percentage of species that are exposed to a concentration above the No Observed Effect Concentration (NOEC). The higher the concentration, the greater the number of species affected. High PAF values do not have to result in noticeable damage, indicating that PAF SHOULD BE UNDERSTOOD AS TOXIC STRESS RATHER THAN AS A MEASURE TO MODEL SPECIES DISAPPEARANCE.

ACIDIFICATION AND EUTROPHICATION

By analyzing the impact of acidification and eutrophication on plants, the Probability Of Occurrence (POO) of a given plant in a given region can be calculated. Based on the POO, a Potentially Disappeared Fraction (PDF) can be calculated:

$$PDF = 1 - POO$$

LAND USE AND TRANSFORMATION

The PDF indicator is also used to model damage from land use and transformation. Two models are used to model this category of damage:

1. local impacts of land use or conversion, related to the change in the number of observed species on that land,
2. regional impacts of land use or conversion, related to the change of natural expanses outside that land.

The ecosystem quality unit is: PDF x AREA x YEAR.

THE DAMAGE (i.e. the occupied land restoration time) increases with the increase in the area and the time of land occupation.

RESOURCES

Only sources of ores and fossil fuels are considered in this damage category. The main element of resource quality is the CONCENTRATION OF RESOURCES. If the energy required for extracting the ore is related to the concentration of the ore, it follows that the more ore is extracted, the more energy will be needed for mining in the future.

In this case, DAMAGE is defined as:

“the amount of energy, the so-called SURPLUS ENERGY, needed to extract 1 kg of ore in the future”.

The resources damage unit is the surplus (excess) energy in [MJ/kg] of extracted material.

Damage from ozone depletion, radioactive substances and resource depletion are occurring globally.

NORMALIZATION AND DETERMINING WEIGHT FACTOR

Three categories of damage have three units. To obtain dimensionless values, NORMALIZATION is applied. When WEIGHTING the three damage categories, human health and ecosystem quality were rated as equally important whereas damages to resources were rated to be half as important. The choice of factors for determining significance depends on the attitude and personality of people, which is why there are THREE DIFFERENT ECO-INDICATOR 99 METHODOLOGIES.

Table 20: Three different Eco-Indicator 99 methodologies [Source: Ostad, 2006]

Prototype	Time perspective	Management style	Attitude towards risk
H – Hierarchist	Balance between short and long time	Control	Risk-accepting
I – Individualist	Short time	Adaptive	Risk-seeking
E – Egalitarian	Very long time	Preventive	Risk-aversive

WEIGHTING

After determining the significance of normalized values of damage categories, these values are combined into a single ECO-INDICATOR VALUE, whose unit is a POINT (Pt), or more often a MILIPOINT (mPt). The absolute value of these points does not matter. Their main purpose is to compare the relative differences between products.

1 Pt = 1 / 1000 EL/person/year

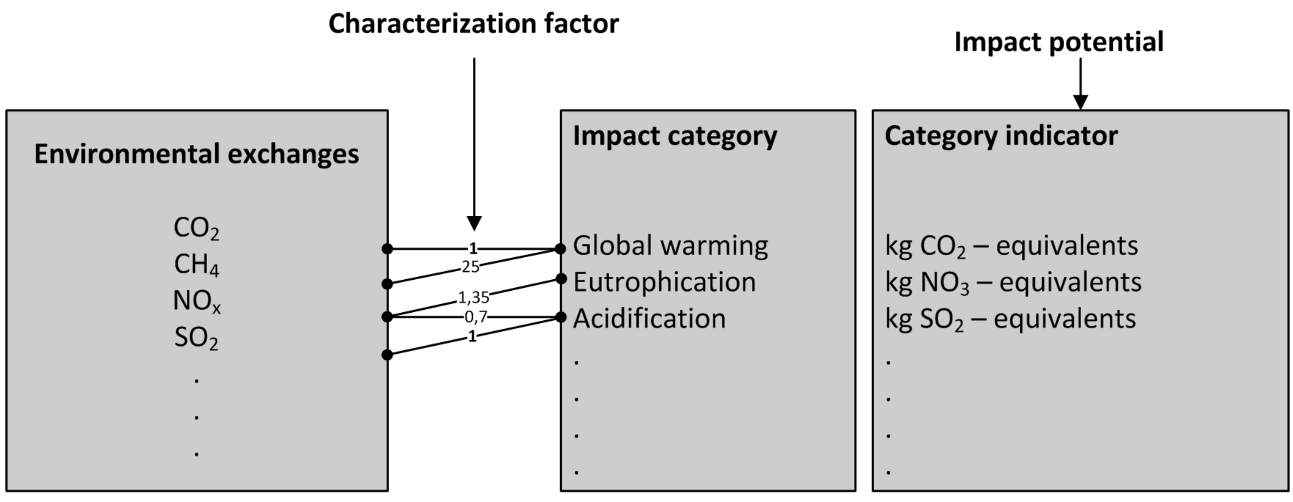
One point (Pt) is a thousandth of the annual environmental load of an average European.

EDIP METHOD

EDIP (Environmental Design of Industrial Products) – is a methodology developed in the period 1991-1996 in Denmark. EDIP method represents the so-called "MID-POINT" APPROACH**.** The method focuses on different environmental categories and sets the initial point in the ecological exchange.

EDIP method considers the following impact categories:

_global warming,
_ozone depletion,
_acidification,
_eutrophication,
_photochemical oxidant creation,
_abiotic resource depletion.



56. Figure_Environmental protection mechanism modeled by the EDIP method [Source: Thrane, Schmidt, 2004]

IMPACT ASSESSMENT

"FILLING" THE LAND WITH WASTE is not possible to model. To cover the impacts from this type of pollution, we introduce four different types of waste:

1. non-hazardous waste (bulk),
2. hazardous waste,
3. slag and ashes (inert waste) and
4. nuclear waste.

To be able to compare the contribution of different impact categories, NORMALIZATION is performed.

Table 21: Criteria for impact assessment according to the EDIP method [Source: Wenzel, 2000]

	Environment	**Resources**	**Working environment**
Global	Global warming Ozone layer depletion		
Regional	Photochemical ozone formation Acidification Increase in the amount of nutrients Permanent toxicity - human toxicity from the water compartment - human toxicity from the soil compartment - chronic ecotoxicity in the water compartment - chronic ecotoxicity in the soil compartment	Fossil fuels: e.g. oil, coal, brown coal and natural gas Metals: e.g. $\mathbf{F}_e$, $\mathbf{A}_l$, $\mathbf{C}_u$, $\mathbf{Z}_n$, $\mathbf{N}_i$, $\mathbf{A}_g$, $\mathbf{A}_u$… Other ores: e.g. lime, phosphates and salts Others	
Local	Ecotoxicity - acute ecotoxicity in the water compartment Human toxicity - human toxicity from the air compartment Landfilling - non-hazardous waste (bulk) - hazardous waste - slag and ash - nuclear waste	Biomass: e.g. wood, straw and grain Water: e.g. groundwater, surface water and water for hydro electric power Others	Cancer due to chemical substances Damage to the reproductive system due to chemical substances Musculoskeletal injuries due to monotonous work Hearing impairments due to noise Grievous bodily harm due to accidents

Reference for normalization is already explained on page 71, as well as background load types for global, regional and local impact categories.

Units for impact categories in EDIP method are given in Table 17, on page 69.

In addition to the explanations given on pages 69-71, further explanations regarding normalization with the EDIP method are presented below.

The YEAR 1990 was taken as a REFERENCE for all of the impact categories. THE BASIC SCALES ARE EXPRESSED PER CAPITA OF THE CONSIDERED AREA, in relation to the world or Denmark, in order to normalize the usual scales. THE ENVIRONMENTAL LOAD (EL) FROM THE AVERAGE PERSON WAS TAKEN AS A REFERENCE FOR NORMALIZATION (N) for the studied product system. The contribution ratio of the product system compared to the average contribution of a person in 1990, was used to scale the contribution of a product to different impact categories.

The final WEIGHTING was performed USING A "DISTANCE-TO-TARGET" APPROACH. The objectives for reducing the Danish contribution to the various impact categories consist of environmental objectives in Danish legislation, environmental action plans as well as international conventions in which Denmark participated. These reduction plans have been normalised to the year 2000 and represent the target for reducing the contribution of society to the various impact categories from 1990 to 2000. The unit for measured values is the "EQUIVALENT OF THE TARGET PERSON" and expresses the acceptable impact of the person in 2000 according to the sum of political goals.

Recent improvements to the EDIP method introduce "platforms" of loads for other European countries, as well as normalization references for European countries and a European average that allows the product to be expressed in the "EUROPEAN PERSONAL EQUIVALENT" unit. The investigation of reduction targets in different European countries permits the development of an average European "equivalent of the target person" for weighting (to determine significance).

Normalization and data collection to perform weighting are also done in China and lead to the "CHINESE EQUIVALENT".

EDIP method is consistent with the international consensus on impact characterization. COOPERATION BETWEEN THE THREE SIDES: INDUSTRY, UNIVERSITIES AND AUTHORITIES, during the development of the method, provided the optimum in practical use as well as scientific depth. In regards with practical use, industry has developed a sense for meaning of different impact categories, what impact and consequences each of them has, how to interpret the values and how to aggregate these values into visible and understandable environmental loads. Operations of normalization and weighting are more scientific than in the function of indicator, where WEIGHTING DEPENDS ON THE SUBJECTIVE ATTITUDE OF PEOPLE TOWARDS THE CATEGORY OF DAMAGE.

QFD AND EQFD METHODS

Methods that also take into account the requirements of consumers (stakeholders) and "translate" them into technical language:

_QFD (Quality Function Deployment) – is an important method for integrating consumer requirements and needs into the product development process. QFD is looking for consumer requirements that are translated into technical design parameters.

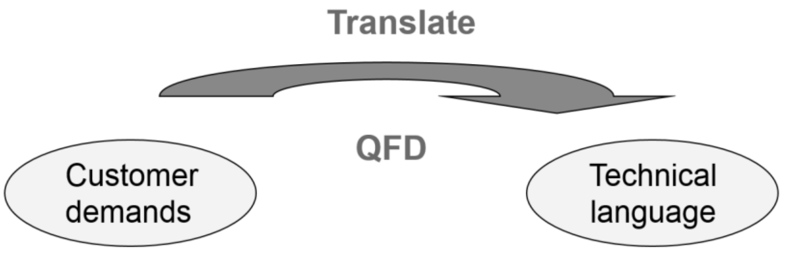
_EQFD (Environmental Quality Function Deployment) – the method helps to identify the most important environmental parameters among the many consumer requirements and stakeholder needs, respectively.

QFD and EQFD methods use ASYMMETRIC SCALE 0-1-3-9 for evaluation. This asymmetric scale helps to clearly assess important requirements.

QUALITY FUNCTION DEPLOYMENT - QFD

THE BASIC QUESTION IS:

How to take into account the requirements of "stakeholders" (shareholders, interest groups) in the processes of improvement and product design ?

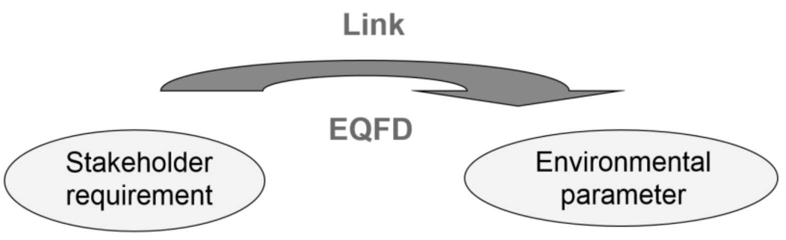


57. Figure_QFD method

The method was devised by *Yoji Akao* in Japan in 1966. The breakthrough was made in 1972 by MITSUBISHI HEAVY INDUSTRIES. The method was first implemented in Europe in 1987.

ENVIRONMENTAL QUALITY FUNCTION DEPLOYMENT - EQFD

This method identifies important ENVIRONMENTAL PARAMETERS AMONG THE different requirements of consumers and "stakeholders".

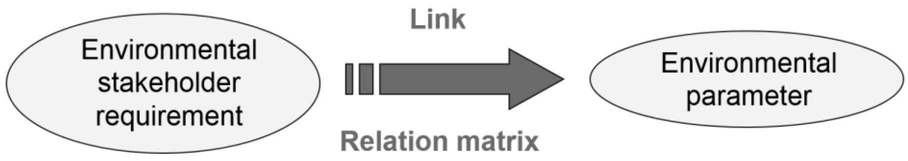


58. Figure_EQFD method

Table 22: Environmental requirements of "stakeholders" [Source: Wimmer et al., 2003]

Safe for the environment
Free of hazardous substances
Lightweight
Durable
Less transport
Energy saving
Easy to use
Easy to maintain
Easy to repair
Easy to recycle
Easy to disassemble
Easy to reuse

A specific product cannot meet all the requirements.



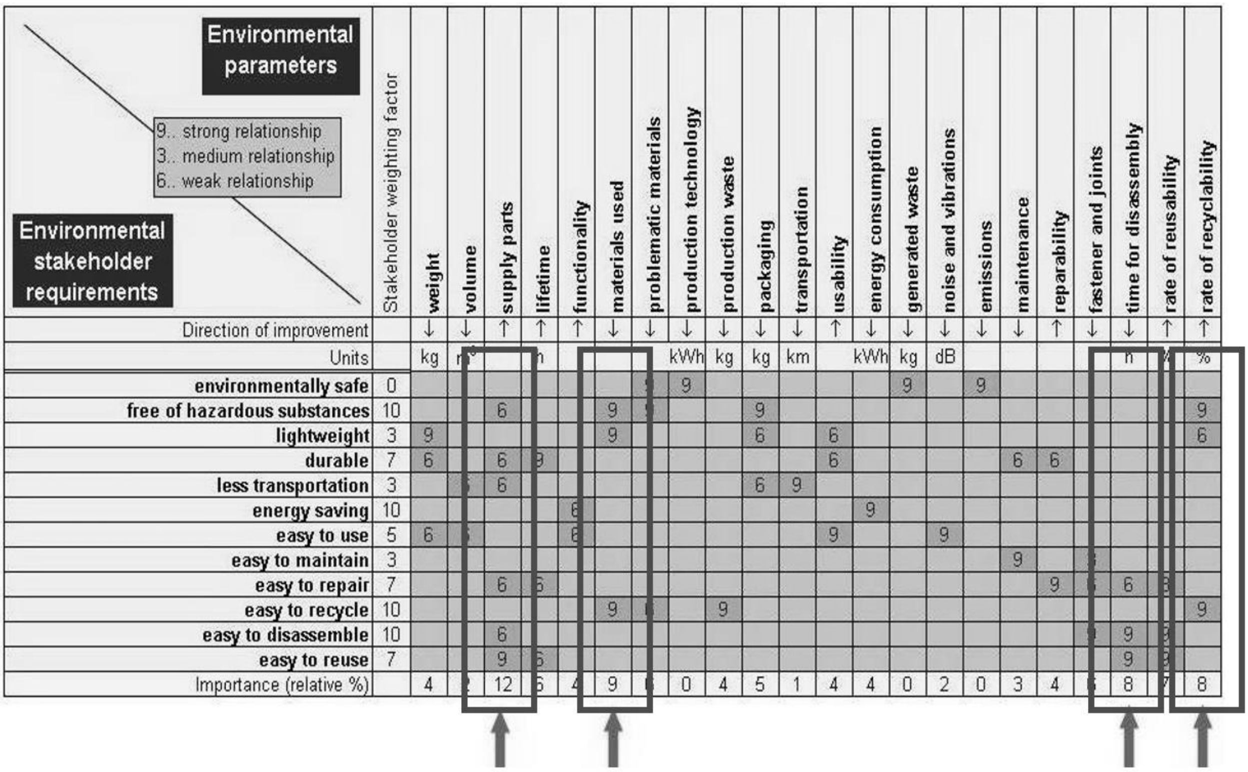
59. Figure_Relation between environmental requirements and parameters

Relations are expressed by evaluating the connectivity factors:

_3 – weak relation,
_6 – medium relation,
_9 – strong relation.

The importance of the “stakeholder” requirements for a particular product is assessed on a 0-10 scale, where:

_0 – not important,
_10 – very important.



Environmental stakeholder requirements	Stakeholder weighting factor	weight	volume	supply parts	lifetime	functionality	materials used	problematic materials	production technology	production waste	packaging	transportation	usability	energy consumption	generated waste	noise and vibrations	emissions	maintenance	reparability	fastener and joints	time for disassembly	rate of reusability	rate of recyclability
Direction of improvement		↓	↓	↑	↑	↑	↓	↓	↓	↓	↓	↓	↑	↓	↓	↓	↓	↓	↑	↓	↓	↑	↑
Units		kg	[illegible]		[illegible]				kWh	kg	kg	km		kWh	kg	dB					h	[illegible]	%
environmentally safe	0							[illegible]	9						9		9						
free of hazardous substances	10			6			9	[illegible]			9												9
lightweight	3	9					9				6		6										6
durable	7	6		6	9								6					6	6				
less transportation	3		[illegible]	6							6	9											
energy saving	10					[illegible]								9									
easy to use	5	6	[illegible]			[illegible]							9			9							
easy to maintain	3																	9		[illegible]			
easy to repair	7			6	6														9	[illegible]	6	[illegible]	
easy to recycle	10						9	[illegible]		9													9
easy to disassemble	10			6																[illegible]	9	[illegible]	
easy to reuse	7			9	6																9	[illegible]	
Importance (relative %)		4	[illegible]	12	6	4	9	[illegible]	0	4	5	1	4	4	0	2	0	3	4	[illegible]	8	7	8

60. Figure_Matrix of relation between “stakeholder” requirements and environmental parameters [Source: Wimmer, Züst, Lee, 2004]

EXAMPLE: QFD MATRIX FOR NOTEBOOK COMPUTERS

A concrete example of the application of the QFD method is a QFD MATRIX (Table 23), which was obtained as a result of the analysis of notebook computers. The study entitled

„An empirical study of constructing a dynamic mining and forecasting system for the life cycle assessment-based green supply chain” was conducted by *Chien-Yung Lai, Chin-Hung Hsu and Hui-Ming Kuo* in 2012. THE SIGNIFICANCE (WEIGHT) of consumer requirements was determined for four periods by the double exponential smoothing-based data mining method. Tables 24 and 25 show the consumer requirements and technical characteristics of the product.

Table 23: QFD matrix for notebook computers

	Weights	EC1	EC2	EC3	EC4	EC5	EC6	EC7	EC8	EC9	EC10
CR1	6.9	9	3	1	3	3	1	3	9	3	3
CR2	5.5				1	1	3		3	9	
CR3	5.8	3	1	1		9	1	3	3	3	3
CR4	4.9	3	9	9	1	1	1	3	3	3	9
CR5	5.3	1			3	9	9		1	9	9
CR6	7.2	3		1	3	9	9		9	9	3
CR7	6.5	3		1	9	9		3	9	9	1
CR8	5.8	9	1	9	3	9	3	3	9	9	9
CR9	5.7		3	1	1				3	3	1
Importance of EC		192.8	93.5	128.4	150.2	306.5	164	89.7	308.6	342.6	215.9

Table 24: Consumer requirements for the matrix in Table 23

Voice of customer	Customer Requirements
CR1	Price or cost
CR2	Operating quality
CR3	Size or weight
CR4	No toxical material released
CR5	Easily disassembly
CR6	Easily maintenance
CR7	Energy saving
CR8	Recyclable
CR9	Speed

Table 25: Technical characteristics of notebook computers relevant to the matrix in Table 23

		Voice of Engineering	Engineering Characteristics
Life cycle assessment-based green supply chain	Raw Material	EC1	Material reduction
		EC2	No dangerous material
	Manufacturing	EC3	Pollution control
		EC4	Low energy exhausting
	Disassembly	EC5	Modularization
		EC6	Tools usage
	Transportation	EC7	Package reduction
	Usage	EC8	Energy saving
		EC9	Maintenance
	Disposal	EC10	Reuse or recycle

SOME OF THE SIMPLIFIED LIFE CYCLE ASSESSMENT METHODS

QUALITATIVE ASSESSMENT OF THE PRODUCT (DESCRIPTION)

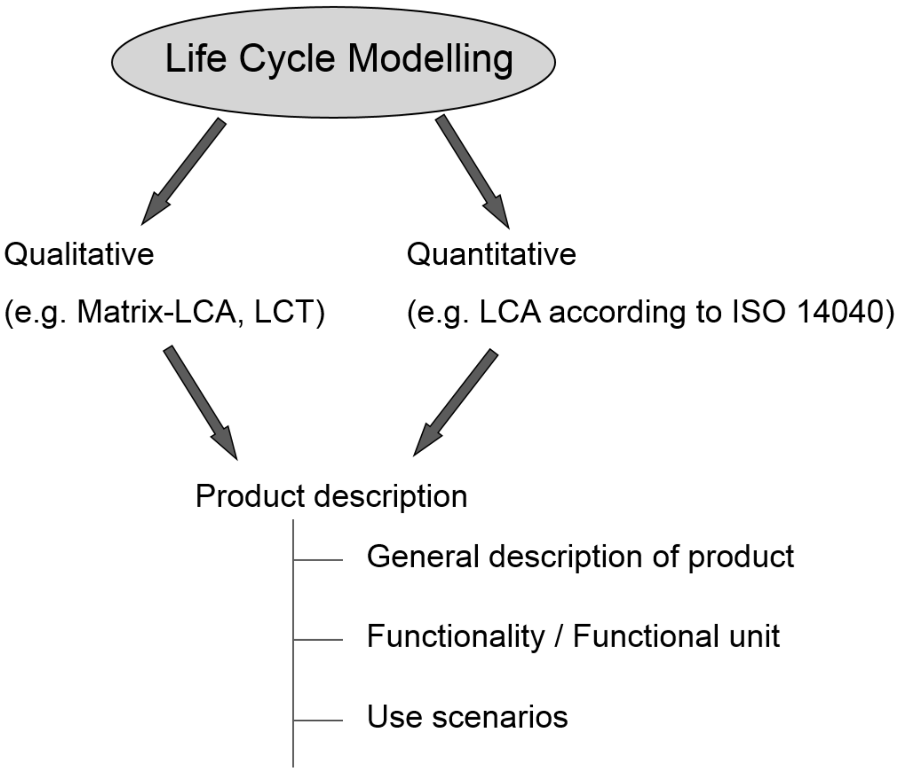
Typically, qualitative data is expressed as a RATING SCALE, e.g. 1 is "BEST" and 5 is "WORST", or relative rating expressions such as "BETTER THAN" or "WORSE THAN". Qualitative data can also be used e.g. for the LCA matrix. A qualitative description of the product provides a first general overview of that product. This can be achieved by using general data such as:

_product name,
_names of the components,
_parts and components that must be ordered from another manufacturer,
_use scenario,
_functionality,
_functional unit,
_...

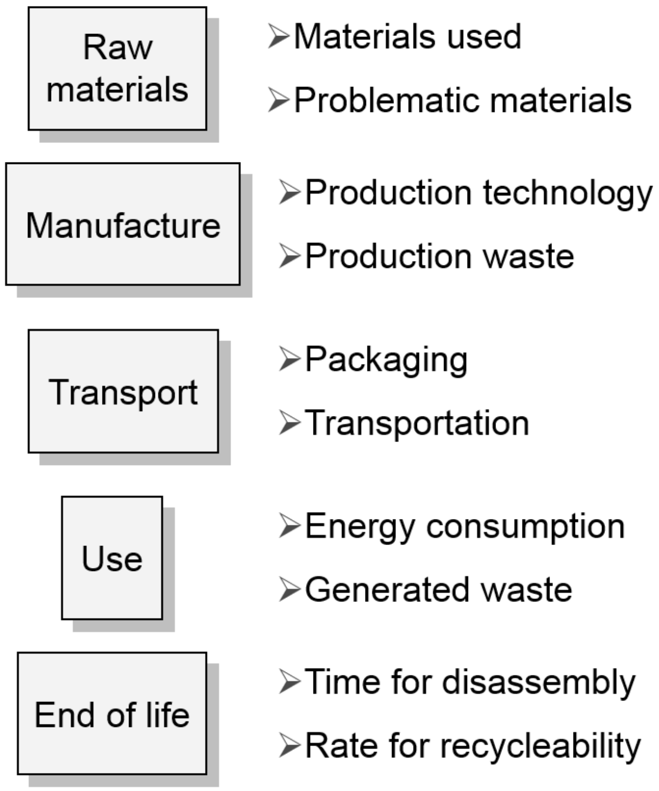
The qualitative description can also include A TEXTUAL DESCRIPTION OF THE PRODUCT, as can be found in the parts of the EPD – Environmental Product Declaration.

To assess the environmental dimension of a product using qualitative data, we need to consider so-called "ENVIRONMENTAL PARAMETERS".

It is very important how the boundaries of the system are chosen!



61. Figure_ Product life cycle modeling

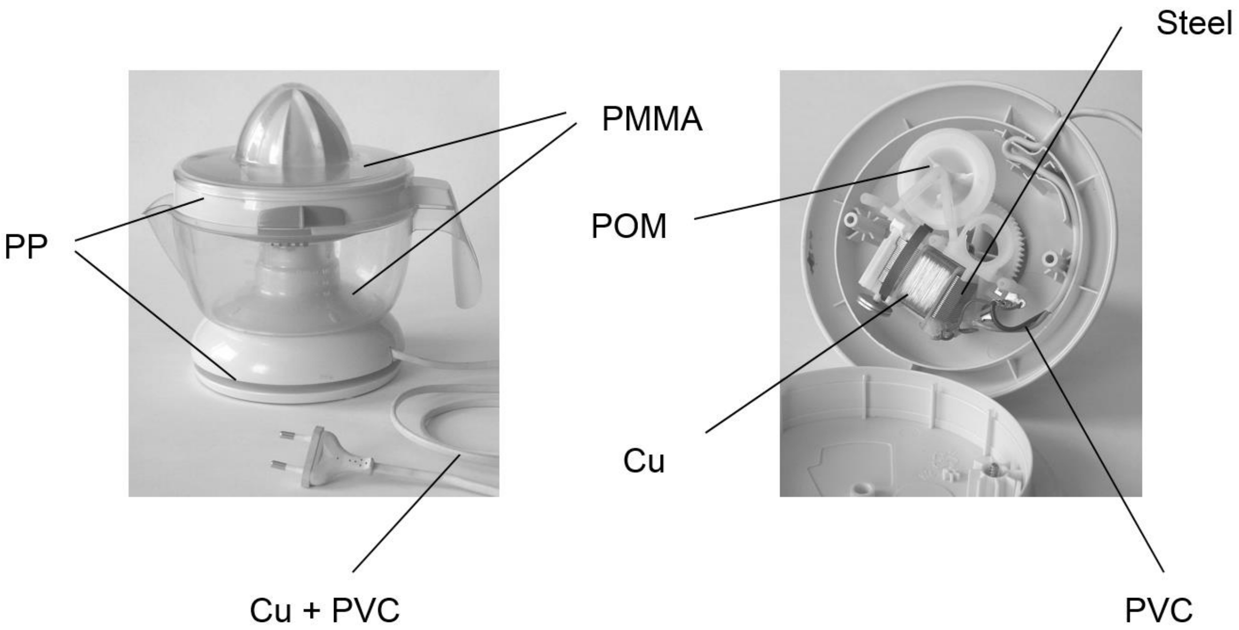


62. Figure_Environmental aspects – environmental parameters at all stages of the life cycle [Source: Wimmer, 2007]

Table 26: Environmental parameters associated with product life cycles [Wimmer, 2004]

Life cycle phase	Environmental parameter
Use of raw materials	✓ Materials used ✓ Problematic materials ✓ ...
Manufacture	✓ Manufacturing technologies ✓ Manufacturing waste ✓ ...
Distribution and packaging	✓ Packaging ✓ Transport ✓ ...
Use of the product	✓ Usability ✓ Energy consumption ✓ Waste accumulation ✓ Noise and vibrations ✓ Emissions ✓ Maintenance ✓ Repairability ✓ ...
End of life	✓ Fasteners and joints ✓ Disassembly time ✓ Rate of reuse ✓ Recyclability rate ✓ ...

EXAMPLE OF A QUALITATIVE ASSESSMENT OF THE PRODUCT: DESCRIPTION OF THE JUICE EXTRACTOR

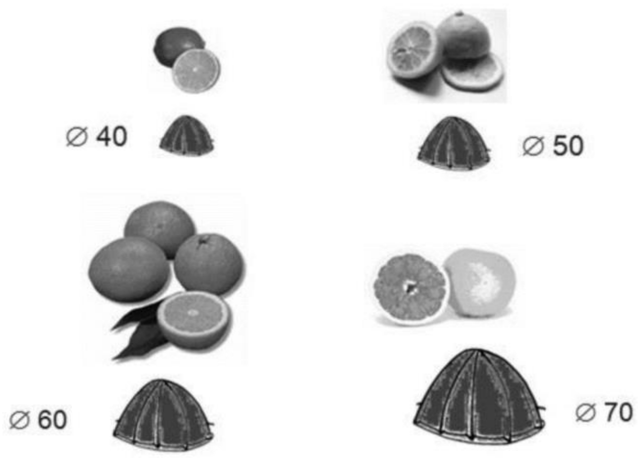


63. Figure_ Juice extractor – main components [Source: Wimmer, 2007]

Table 27: General information on a juice extractor [Source: Wimmer, 2007]

General information (qualitative and quantitative)	
Product name	Juice extractor
Product weight	705 g
Weight of the product with packaging	1,055 g
Dimensions	Height: 192 mm Maximum diameter: 82 mm
Volume capacity	600 ml – 1,250 ml (depending on model)
Components	Motor: 85 g Pressing cap: 135 g Cap: 170 g Juice container: 190 g Cable: 65 g Packaging: 345 g
Outer parts	Cable, motor
Use scenario	Once a day, 50 weeks a year for 5 years
Lifespan	5 years
Functionality	The squeezed juice falls directly into the container through the sieve. The juice extractor is switched on by contact, upon pressing the fruit against the cone, and operates as long as the contact force exists.

The juice extractor has the ability to extract 45% of the orange juice content; 55% IS THROWN AWAY! An ideal juice extractor would extract 100% of the juice content. DIFFERENT CONE SIZES guarantee optimized juice extraction for different types of fruit.

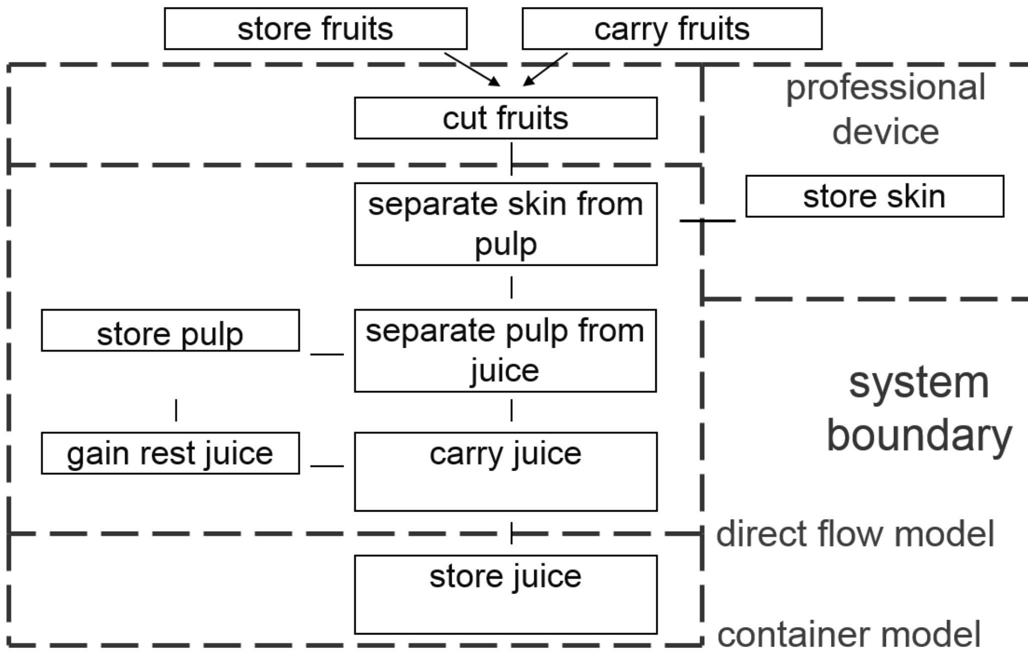


64. Figure_Different cone sizes [Source: Wimmer, 2007]

Table 28: Description of environmental parameters for the juice extractor [Source: Wimmer, 2007]

Environmental parameter	**Explanation (qualitative)**
Use of raw materials	
Materials used:	ABS, SAN, PP, PS The motor contains metal parts. Cable contains copper
Manufacture	
Manufacturing technologies:	Mainly injection molding
Manufacturing waste:	Packaging of external parts, sprue bushes of injection moulding
Distribution and packaging	
Packaging:	Cardboard boxes
Transport:	Truck
Use of the product	
Usability:	Extracting juice, collecting juice, cleaning
Energy consumption:	15 W
Waste produced:	Fruit pulp (biological waste), orange peels
Noise and vibrations:	Gears are not damped, so they can cause a lot of noise during use
Maintenance:	Washing after use, dishwashing detergent required
Repairability:	Extractor changes completely in case of damage
End of life	
Fasteners and joints:	Connectors
Disassembly time:	It is possible to disassemble in less than 2 minutes, the motor remains in one piece
Rate of reuse:	The motor, after inspection, can be reused
Recyclability rate:	Approximately 40%

SETTING THE SYSTEM BOUNDARIES FOR THE JUICE EXTRACTOR

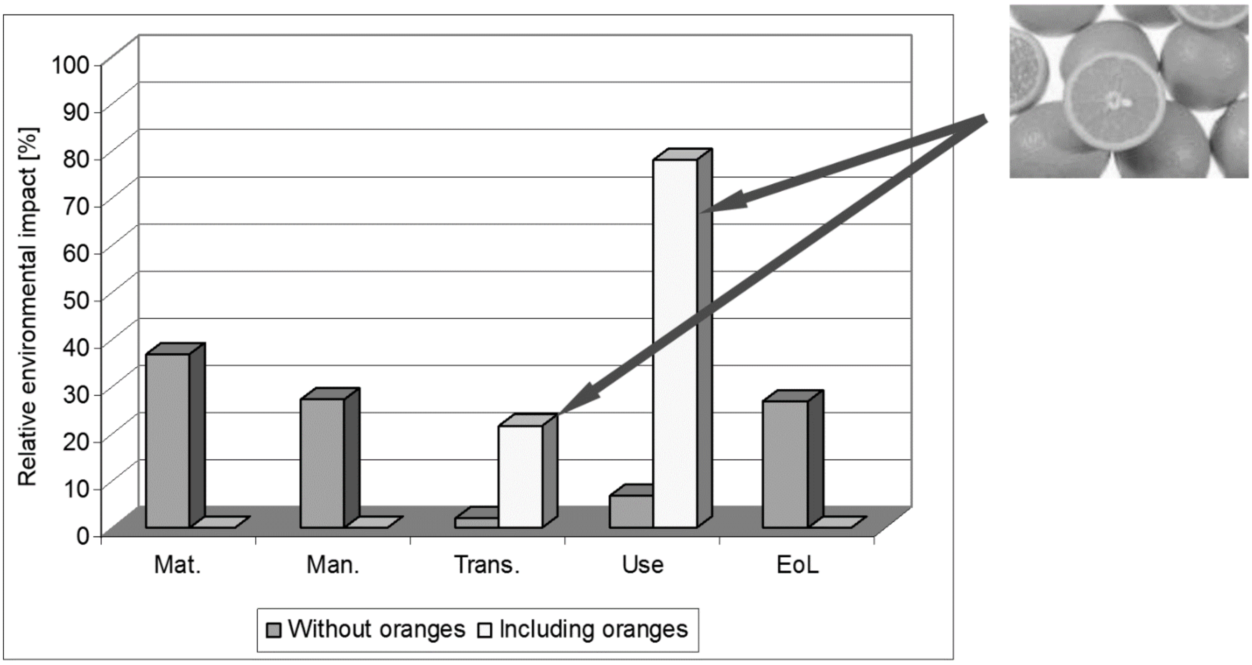


65. Figure_Setting the system boundaries for the example of a juice extractor

To get juice, the juice extractor needs fruits, e.g. oranges.

If oranges are taken into account, we have:

_origin: Brazil and/or Spain,
_transport: 10,000 km by ship, 2,000 km by truck,
_irrigation: 1,000 litres/kg.
_average weight of orange: 150 g
_average juice content in each orange: 105 g
_on average, an extraction of 750 ml of juice requires 11 oranges (this is an empirical data).



66. Figure Comparison of environment profiles: with and without oranges

MET-MATRIX (ENVIRONMENTAL IMPACT EVALUATION)

THE MET-MATRIX is a simple and easily applicable method of qualitative product evaluation. MET stands for Material – Energy – Toxicity. It gives a first impression of how the environmental impact, at different stages of the product life cycle, can be assessed and which stages are important and which are not so significant.

Table 29: Standard MET-matrix [Source: Wimmer, 2007]

	Raw materials	Manufacture	Distribution and packaging	Use	End of life
Material					
Energy					
Toxicity					

Table 30: Modified MET-matrix [Source: Wimmer, 2007]

	Raw materials	Manufacture	Distribution and packaging	Use	End of life
CO_2 - eq					
SO_2 - eq					
...					

In addition to qualitative evaluation, the MET-MATRIX also allows quantitative evaluation of products.

In Table 19 on page 74, Contribution Analysis is presented in the form of a modified MET-MATRIX.

EVALUATION OF ENVIRONMENTAL IMPACT

HOW CAN THE ENVIRONMENTAL IMPACT BE MEASURED?

One isolated value cannot be sufficient to assess the environmental impact, but A COMBINATION OF DIFFERENT PARAMETERS is necessary (e.g. consumption of energy, materials and non-renewable resources).

WHEN IT COMES TO TOXIC SUBSTANCES, SMALL AMOUNTS HAVE BIG IMPACT!

THE MET-MATRIX is an easy way to obtain an environmental impact evaluation, and is particularly suitable for finding "HOT SPOTS". With it, both qualitative and quantitative description can be realized. THE MET-MATRIX gives the first suggestions for "hot spots".

Table 31: Finding hot spots using a MET-matrix on the example of a juice extractor [Source: Wimmer, 2007]

	Raw materials	**Manufacture**	**Distribution and packaging**	**Use**	**End of life**
Material	Metals (C_u, steel) Plastic (PP, PVC, ABS...)	Injection tools, motor, cables, lubricants, coolants	Packaging	Fruit, water, detergent,	Process materials, recycling of materials
Energy	Energy for refining or granulating	Injection molding, metal processing	Fuel (diesel)	Electricity	Energy for recycling Recovery of energy
Toxicity	Emissions during extraction	Emissions	Emissions	-	PVC, electrical parts

Table 32: Compatibility of plastics in juice extractor – related to end-of-life options [Source: Wimmer, 2007]

	PMMA	PP	POM	PVC	ABS	PE	PS
PMMA	☺						
PP	☹	☺					
POM	😐	😐	☺				
PVC	☹	😐	☺	☺			
ABS	☺	☹	😐	😐	☺		
PE	☹	☹	☹	☹	☹	☺	
PS	☹	☹	😐	☹	☹	☹	☺

To obtain effective product improvement strategies:

_one should know which stage of the life cycle contributes most to the impact on the environment,
_what caused the impact at each stage of the life cycle,
_why do impacts occur,
_what are the key environmental impact parameters.

QUANTIFIED DATA IS REQUIRED FOR IMPACT ASSESSMENT!

Table 33: Energy values for the materials from which the juice extractor is made [Source: Wimmer, 2007]

Material	[MJ/kg]	Weight [kg]	Result [MJ]
Polypropylene (PP)	78	0.120	9.36
Steel	32	0.085	2.72
Copper (C_u)	65	0.065	4.23
Polymethyl methacrylate (PMMA)	95	0.250	23.75
Polyoxymethylene or acetal (POM)	105	0.050	5.25
Polyvinyl chloride (PVC)	70	0.030	2.1
Polyethylene (PE)	80	~ 0.035	2.8
Polystyrene (PS)	96	~ 0.035	3.36
Acrylonitrile butadiene styrene (ABS)	100	~ 0.035	3.5
Total		0.705	**57.07**

Table 34: Energy values for the manufacturing phase [Source: Wimmer, 2007]

Manufacture	[MJ/kg]	Weight [kg]	Result [MJ/piece]
Injection molding	78	0.555	43.29
Metal forming	32	0.15	4.8
Total		0.705	**48.09**

Table 35: Energy values for transport of juice extractor [Source: Wimmer, 2007]

Transport of juicer	Distance [km]	[MJ/tonne·km]	Result [MJ/piece]
Truck	3,000	1.5	**4.5**

Table 36: Energy values for the use phase [Source: Wimmer, 2007]

Use	[kWh] per use	[kWh] over the lifetime
Energy consumption	$8.06 \cdot 10^{-4}$	**4.23**
	[MJ/kWh] on average	[MJ] over the lifetime
Energy consumption	10	**42.3**

Table 37: Energy values for the EoL phase of plastic parts of the juice extractor [Source: Wimmer, 2007]

End of life	Weight [kg]	[MJ/kg]	Result [MJ]
Recycling/re-melting of plastics	0.555	-20	**-11.1**

Table 38: Production and transport of oranges [Source: Wimmer, 2007]

Manufacture	[MJ/m³]	[m³]	Result [MJ]
Oranges (saltwater treatment)	13.0	1	**13.0**
Oranges (pump irrigation)	1.8	1	**1.8**
Transport	Distance [km]	[MJ/tonne·km]	Result [MJ/kg]
By ship from Brazil	10,000	0.11	**1.1**
By truck from Spain	3,000	1.5	**4.5**
By truck to the consumer	2,000	1.5	**3.0**

Table 39: Data for mixed oranges [Source: Wimmer, 2007]

	Weight/ piece	Spain 75%	Brazil 25%	Transport by truck	Total
Weight	0.150 g	1.2375 kg	0.4125 kg		1.650 kg
Transport		5.57 MJ	0.45 MJ	4.95 MJ	10.97 MJ
Irrigation					24.42 MJ
Total MJ					**35.39 MJ**

Table 40: Total energy required for oranges and juice extractor, combined [Source: Wimmer, 2007]

		Raw materials	**Manufacture**	**Transport**	**Use**	**EoL**	**Total**
Juice extractor	[MJ]	57.07	48.09	4.5	42.3	-11.1	141
Oranges	[MJ]	-	1750·0.55·24.42= 23,504.25	1750·0.55·10.97= 10,558.625	-	-	34,063
Total	[MJ]						**34,204**

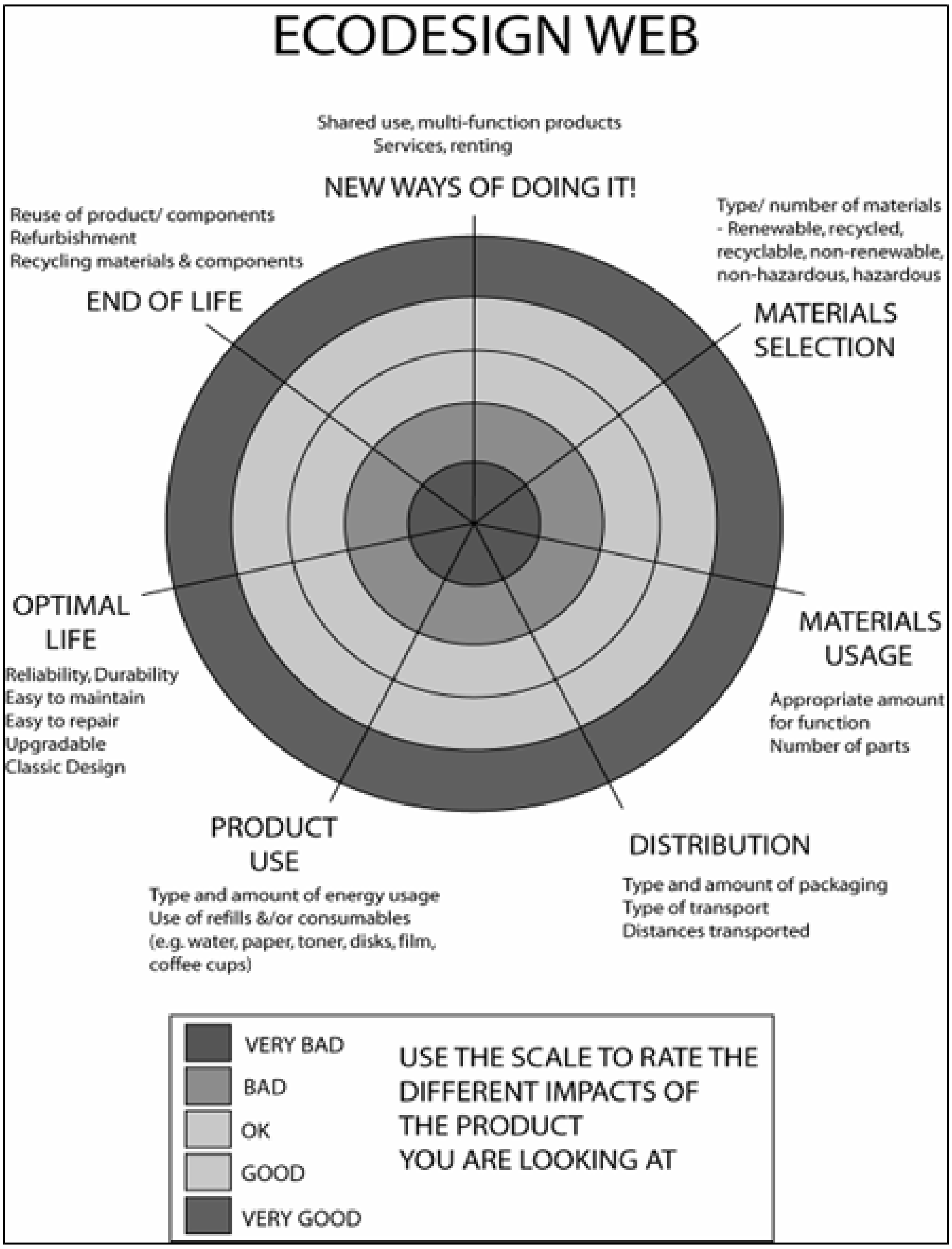
Use scenario:

The juice extractor is used once a day, 50 weeks/year for 5 years, which gives a total use of 1,750 times during the life cycle. Losses due to inefficiency of the device are equal to 55%, 24.42 MJ is used for irrigation, and 10.97 MJ is used for transport, see Tables.

Conclusion: Orange waste contributes the most to the environmental impact of the juice extractor!

ECODESIGN WEB

AN ECODESIGN WEB is something like a visual checklist that allows for a quick evaluation of the design.



67. Figure_Ecodesign web [Source: Loughborough University, 2005]

Table 41: Advantages and disadvantages of the Ecodesign web [Source: Morris, 2007]

PROS ☺	CONS ☹
• Provides an opportunity to fully reconsider the product/service, e.g. rental service • Easy to use • Fast product evaluation • Good means of communication	• Inability to quantify • Different users can return different webs for the same product, because the points on the web are evaluated

ECOLOGICAL FOOTPRINT

Based on calculations that say that there is an average of 1.8 gha (global hectares) of biologically productive land per person, but an average of 2.2 gha is used per person. Some countries sometimes have a much bigger ECOLOGICAL FOOTPRINT than Earth's capacity. This data can be produced for SPECIFIC REGIONS, both THEORETICALLY FOR PRODUCTS AND PRODUCT SYSTEMS.

Table 42: Advantages and disadvantages of the Ecological footprint [Source: Morris, 2007]

PROS ☺	CONS ☹
• Land use measure is a unit that most people can understand • Can document the use of nature by the company • Data is easily accessible	• Does not show individual environmental impacts, e.g. global warming, human poisoning • Oversimplifies the situation? • Rarely used for individual products

ECOLOGICAL RUCKSACK

It is a useful tool, which is relatively easy to calculate, and is almost self-explanatory: each product carries a certain “ECOLOGICAL BURDEN” in a theoretical “RUCKSACK”.

The ecological rucksack is defined as:

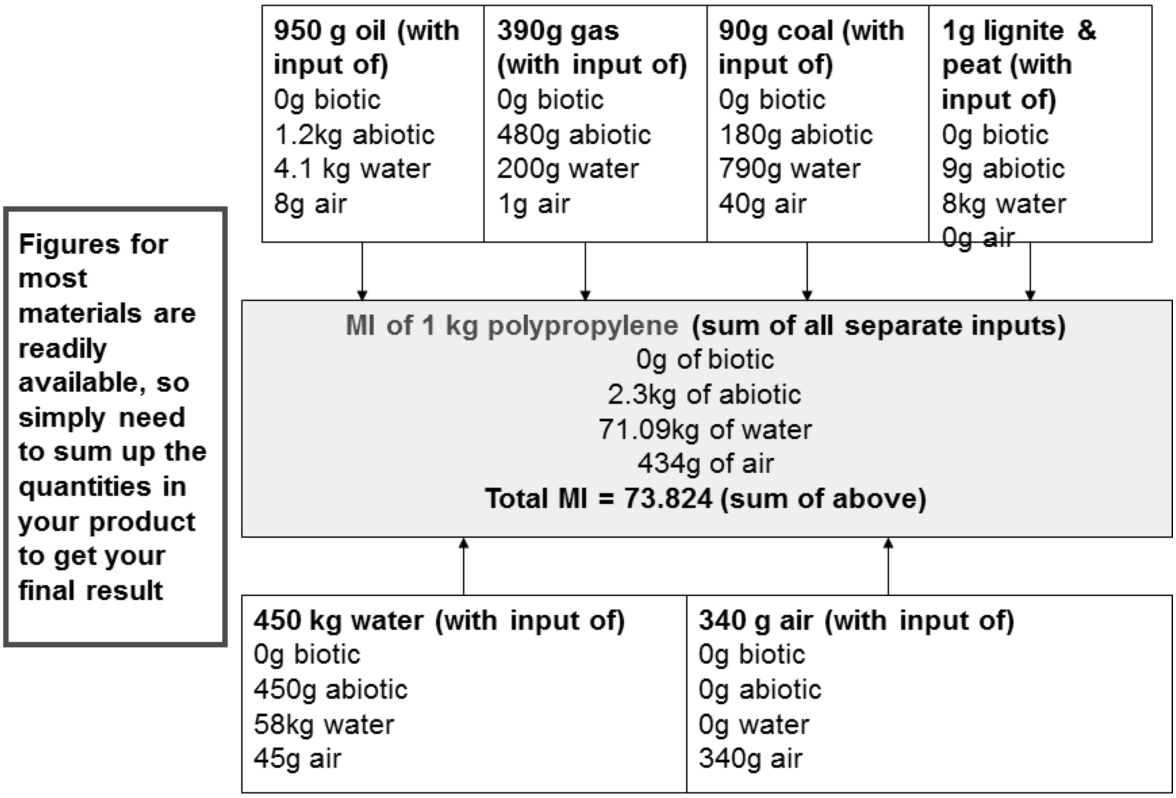
“The total quantity (in kg) of the natural material that is disturbed in its natural setting and used to create a finished product (minus the actual weight of the product)”.

Displaced (disturbed) materials are divided into four categories:

1. abiotic,
2. biotic,
3. water,
4. air.

Relative to the concept of MATERIAL INTENSITY: the final result is called MI (Material Intensity).

The ecological rucksack makes IT EASY TO COMPARE PRODUCTS.



68. Figure_Ecological rucksack - example [Source: Morris, 2007]

MIPS – MATERIAL INTENSITY PER UNIT OF SERVICE

Very connected to the ECOLOGICAL RUCKSACK, but it is calculated FOR THE UNIT OF SERVICE that the product can provide during its service life.

E.g. the ecological rucksack can be calculated for all components of the car (the MI result), but to calculate MIPS, the MI result should be divided by the total number of expected kilometers traveled or the actual life span.

You can see the RELATIONSHIP WITH THE FUNCTIONAL UNITS in the LCA, but the tool is not so comprehensive.

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Ecodesign strategies and LCA

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